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Advanced Envelope Systems for Factory Built Homes

California Energy Commission

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PREFACE

The California Energy Commission's Energy Research and Development Division supports energy research and development programs to spur innovation in energy efficiency, renewable energy and advanced clean generation, energy-related environmental protection, energy transmission and distribution and transportation.

The Energy Research and Development Division conducts public interest research, development, and demonstration (RD&D) projects to benefit California. The Energy Research and Development Division strives to conduct the most promising public interest energy research by partnering with RD&D entities, including individuals, businesses, utilities, and public or private research institutions.

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- Reducing greenhouse gas emission in the electricity sector at the lowest possible cost.
- Supporting California's loading order to meet energy needs first with energy efficiency and demand response, next with renewable energy (distributed generation and utility scale), and finally with clean, conventional electricity supply.
- Supporting low-emission vehicles and transportation.
- Providing economic development.
- Using ratepayer funds efficiently.

Advanced Envelope Systems for Factory Built Homes is the final report for the Advanced Envelope Systems for Factory Built Homes project (contract number PIR-12-028) conducted by The Levy Partnership. The information from this project contributes to the Energy Research and Development Division's Building Energy Efficiency Research & Technology Grant Program.

For more information about the Energy Research and Development Division, please visit the Energy Commission's website at www.energy.ca.gov/research/ or contact the Energy Commission at 916-327-1551.

ABSTRACT

The Advanced Envelope System project explored advanced envelope designs for the manufactured housing industry, and examined how best to provide factory homebuilders with high performance, cost-effective alternative envelope designs. These technologies will play a central role in meeting more stringent energy code requirements incorporating the more rigorous International Energy Conservation Code (IECC) 2012 levels - requirements consistent with site built and modular housing. This adds importance to identify envelope technologies the industry can implement in the short timeframe and meet the thermal requirements based on 2012 IECC standards. Given the affordable nature of manufactured homes, first cost is a major consideration in developing the new envelope technologies.

This multi-year effort first identified technologies for building high performance wall and roof systems, then focused on developing viable product designs, manufacturing strategies, addressing code and structural issues, and cost analysis of the selected options. The team also examined material selection, manufacturing and cost analysis, and prototyping and testing. The designs with the greatest market potential, were evaluated and analyzed to begin production and design hurdles to commercialize.

Keywords: California Energy Commission; factory built housing; manufactured housing; modular housing; research, design, and development; advanced envelope research; energy efficiency; envelope technology; advanced wall strategy; walls with exterior sheathing; continuous exterior insulation; advanced roof design; dense-packed attic roofs; cool roofs; radiant barrier system; test huts.

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EXECUTIVE SUMMARY

Introduction

Since the late 1970s, California has reduced per person energy use by improving residential building performance with strict building standards. Under the Title 24 Building Efficiency Standards, builders were exposed to new and innovative technologies and modified their building practices to reach higher energy standards. Research conducted by public and private agencies focused on creating building technologies for on-site constructed buildings. The net effect was a nearly unprecedented rise in the level of residential efficiency, placing California at the forefront of national efforts to reduce energy use. Unfortunately manufactured housing stayed on the sidelines and energy performance changed only modestly and incrementally for these types of structures.

Manufactured homes are the United States' choice for unsubsidized, affordably priced homes. According to the Bipartisan Millennial Housing Commission, manufactured homes account for about 72 percent of the nation's new affordable housing. This industry fills an important niche in the market by producing quality homes at a much lower cost than site built.

Unlike homes built under California's building energy efficiency standards, all manufactured homes produced in the nation conform to one set of standards, the Manufactured Housing Construction Safety Standards enforced and maintained by the United States Department of Housing and Urban Development. These standards (the HUD Code), first established in 1976,preempt California building energy efficiency standards and are less stringent. These codes, however are positioned to change and when approved by HUD will move to the more rigorous International Energy Conservation Code (IECC) 2012 levels. These new requirements are more on par with those for site-built and modular housing.

California has more than 500,000 manufactured homeowners who can afford their homes *because* they are manufactured. Any increase in price even of only a few thousand dollars might mean not qualifying for a home loan or not being able to afford basic amenities. The industry competes on price and small differences in cost impact sales. And the value equation associated with greater energy efficiency is not well understood by either buyers or sellers of manufactured homes. As a result most manufactured homes just comply with the minimum federal standards.

This disconnect between California's Title 24 standard and the HUD Code for manufactured homes impacts the state's efforts to reach ambitious energy goals. Encouraging energy innovation in factory built homes to develop and bring to market "leap frog" advances in emerging envelope technologies closes the energy performance gap. Additionally it improves affordability for those new homebuyers most in need of managing and minimizing homeownership costs.

Project Purpose and Results

The project team examined California's factory built housing industry looking to improve energy performance by developing and commercializing the next generation of wall and roof envelope designs. The team recognized today's factory built homes are not typically associated with superior energy performance. As with industrialized housing in other parts of the world, factory builders can and should be a leader to reduce energy use, establishing a model for others in the home building business to emulate.

Specific project objectives included:

- Develop new wall and roof component designs that, from an energy perspective, are high performance, cost effective and add minimally to first cost.
- Involve the key industry stakeholders in the development process so they share ownership of the results, a precondition for gaining widespread and immediate market acceptance. The expectation is the new construction methods pioneered by this project will be standard practice in California within five years of project completion.

Results

The Advanced Envelope Systems research project successfully developed innovative methods for constructing high performance walls and roofs for manufactured homes. The technologies included methods to achieve significant improvements in roof and wall insulation technologies and applying cool roof principles for home placed in cooling dominated climates.

The team combined innovative design with current engineering in the design- development process, leveraged the advantages afforded by off-site factory production and rapid commercialization. Efforts were made in the manufacturing analysis and product refinement, performance testing under controlled conditions using test structures and associated analysis and demonstrating these technologies in customer-sold homes. These results provide industry with cost-effective solutions for meeting the impending changes to the HUD/DOE energy code.

Manufactured housing stakeholders were successfully engaged as research partners, critics and contributors of products and expertise. These timely and insightful investments contributed to the success of the research and developments effort and their involvement will facilitate the industry adopting these advanced envelope technologies.

Benefits to Californians

Compared to current construction methods, the new designs will lead to less energy use. Applying these advanced assemblies developed through this research is estimated to reduce the annual energy use for a single gas-heated manufactured homes by an average 105 therms and 1,844 kWh. For electrically-heated homes, depending on location, annual savings ranges from 243 to 4,710 kWh.

With new envelope technologies cooling equipment can be downsized between ½ and 1 ton per home and an estimated reduction in CO_2 emissions. Assuming 1,000 manufactured homes built using the envelope advances described in this project, it is estimated that greenhouse gas emissions will be reduced by 1,296 metric tons of CO_2e using emission factors from the California Air Resources Board, California Climate Investments Program.

By 2025, implementing the advanced assemblies statewide is projected to provide homeowners energy cost savings of $18,755,625 for gas heated homes and $40,641,125 for electric heated homes.

CHAPTER 1: Introduction

The Advanced Envelope Research effort aimed to provide factory homebuilders[1] with high performance, cost-effective alternative envelope designs. In the near term, these technologies will play a central role in meeting more stringent energy code requirements. For manufactured homes, the thermal requirements, last updated by statute in 1994, are positioned to move to the more rigorous International Energy Conservation Code (IECC) 2012 levels. These requirements are on par with those for site-built and modular housing. This places added importance on identifying envelope technologies that the industry can implement in the near term.

Thus, the primary goal of this research is to develop advanced envelope designs that meet the thermal requirements of the 2012 IECC standards. Given the affordable nature of manufactured homes, impact on first cost is a major consideration in developing the new envelope technologies.

Background

While the energy efficiency of residential construction in California continues to set the standard for the nation, factory built homes – specifically manufactured housing envelope construction – has not changed appreciably in the last fifteen years. Despite its importance to homebuilding in the state and the intrinsic value of reducing energy use for manufactured homes buyers that make up a major portion of the affordable housing market, innovation in the industry lags the rest of the building industry. The reasons include:

- Scientific and technological: Current methods of building envelope systems are antiquated and improvements in design require collaborative research. Currently, technologies are developed by product producers that pursue the proprietary advantages for individual materials. They are not equipped to take an integrated approach to redesigning entire envelope components, such as roofs and walls, the subject of this research. It is left to the building companies themselves to patch together materials and products, a task that they are not well-positioned to master. This stymies innovation.
- Institutional: The home building industry generally, and manufactured housing specifically, has no tradition of research and product innovation, except in meeting code requirements.

[1] Factory builders are defined as companies that produce homes off-site in production facilities. These companies produce two types of homes: "manufactured" that meet the national preemptive code promulgated by U.S. Dept. of HUD (not Title 24) and "modular" that meet local building codes. The vast majority of factory built homes in California are manufactured homes.

- Institutional: The standards that guide manufactured housing are set by the United States Department of Housing of Urban Development (HUD), not the state. The standards, including the energy portions, were last updated in 1994.
- Institutional: Code agencies are similarly reluctant to accept new building methods and need objective engineering analysis to support any proposed changes.
- Market: The market is conservative and reluctant to accept and suspicious of change. Individual companies that attempt to bring new technologies to market face significant obstacles that would be easily overcome if they worked in concert with other companies.
- Cost and financial hurdles: Factory builders target affordable home buyers where cost is king and increasing first cost is likely to depress sales. This creates a negative feedback loop where home producers are reluctant to add costs even though the result is likely increase home affordability (increase in energy efficiency savings more than offsets the increase in loan costs) for fear of losing market share.

These barriers are not addressed in this project because there is no entity that brings together these potentially common interests to work toward shared solutions. Without an external impetus and focus on concrete goals, such as dramatic improvements in energy performance, these companies have no mechanism for moving forward together. However, this project hoped to develop new wall and roof component designs that add minimally to first cost while involving the key industry stakeholders in the development process so they share ownership of the results and can move forward in concert together.

CHAPTER 2: Research Goal and Objectives

The Advanced Envelope Systems research project developed new and innovative methods for building roof and wall systems to reduce energy use in factory built homes and take steps to transition the market in California to the new methods. This was accomplished through a concurrent engineering approach that involved key industry leaders and all of the factory home producers in the state.

Objectives of the Research Project

This research project aimed to develop new roof and wall system solutions that would achieve the following:

- Develop for factory use roof and wall designs that use continuous exterior insulation.
- Have an annualized energy cost (total cost of ownership) markedly lower than current construction methods (i.e. monthly energy savings exceed monthly incremental loan costs) for homebuyers.
- Reduce annual heating and cooling energy use when compared to current manufactured home construction. Energy savings that were calculated based on both simulation and data analysis of test huts with prototypes.
- Target to reduce carbon dioxide-equivalent (CO_2e) emissions and reduce cooling equipment size, and associated loads.
- Build demonstration homes that showcase the construction techniques developed for the new envelope technologies and the associated energy savings.

At the conclusion of the research, it was expected that one or more factory builders will, with the technical guidance of the project team, begin tooling up to use the new designs.

Technical Steering Committee

The Technical Steering Committee (TSC) was a group of industry experts, involved in this research project that provided timely and insightful guidance on the research tasks. Meetings were conducted with the TSC throughout the effort to solicit feedback on the work.

The TSC was composed of professionals drawn from the factory building industry that possess technical expertise and a deep knowledge of and experience with the construction of factory built homes, including engineering, building science and home production. The TSC assisted in establishing design criteria, product design constraints, cost parameters, and other factors that helped frame the scope of the design work; provided guidance in research direction, including approach to the research, product needs and design constraints and coordination with other efforts; critiqued interim products, evaluated barriers to implementation and suggested design directions; assisted in identifying plants willing to serve as demonstration/prototyping partners; created a dialogue within their company about how the technology will be adopted; reviewed deliverables and provided specific recommendations for needed refinements; and, provided recommendations regarding information dissemination, market pathways or commercialization strategies relevant to the research products.

The members of the TSC included:

- Michael Wade
  Director of Manufacturing Operations Cavalier Homes
  (256) 747-7504
  mwade@cavhomesinc.com

- Robert Garcia
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  (865) 380-3362
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- Bert Kessler (decd.)
  Vice President, Engineering Palm Harbor Homes
  (972) 763-5044
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- Jeff Legault
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  (703) 558-0654
  lstarkey@mfghome.org

Research Process

The Advanced Envelope Systems research project was a multi-year development effort broadly divided into three phases as follows:

- Phase 1, Design and development: commenced by identifying and screening design options for improving envelope thermal performance and establishing their economic and technical viability in the factory setting. This was followed by resolving barriers to implementation of the technologies, including thermal, structural, and cost analysis, and developing a viable product design.
- Phase 2, Prototyping and testing: consisting of product/technology and process mock ups, manufacturing process evaluation, code compliance and market assessment, and laboratory and diagnostic testing and evaluation.
- Phase 3, Technology transfer and outreach: focusing on dissemination activities and commercialization plans for making the envelope technologies standardized processes in the manufactured housing industry.

CHAPTER 3: Walls

Advanced wall designs were developed with the goal of meeting the prescriptive requirements of the IECC 2012 standards. The technical team followed an iterative process of selecting and eliminating advanced wall solutions in collaboration with the Technical Steering Committee.

Following a preliminary design development of the seven identified options, a qualitative assessment was conducted for the selected technologies. The advisory committee and industry experts rated the options and selected the following for subsequent research:

- SIPs for walls.
- Stud walls with exterior continuous insulation (CI).
- Flash and batt wall construction.

The three concepts were further developed and refined. The technical team and the industry advisory committee discussed the findings, identifying those that were most cost effective and had potential wide market appeal and application (potentially attractive to most manufacturers). Subsequently, one technology – based on the use of continuous exterior sheathing combined with batt insulation – was deemed by the committee as having the greatest commercial potential.

The following section discusses the specifications and design of the advanced wall solution - stud walls with continuous exterior CI.

Wall Performance Specifications

The industry committee developed a detailed set of wall performance specifications as guidance to participating insulation suppliers in recommending design options. These were considered ideal attributes that potentially would be satisfied by a single product incorporated into the overall wall design. Insulation suppliers were encouraged to recommend composite panel concepts based on their proprietary materials that satisfied as many of the conditions as possible. The goal in packing multiple attributes into a single product was to minimize the number of individual products that must be purchased, inventoried, and installed by the plant, saving cost in both handling and main line construction time. The desired attributes are described in Table 1.

Table 1: Advanced Wall Performance Attributes

Properties	IECC Climate Zone 5		IECC Climate Zones 6, 7, and 8	
	Reference Design	**Design 1**	**Design 2**	**Design 3**
Required Properties				
Insulative Sheathing R-Value	Not applicable	R-5	R-10	R-5
Vapor Management[1]	Class I/II vapor retarders (VR) on inside.	Preferred: Class I/II insulative sheathing on exterior with Class III VR on inside. Alternative:[2] Class III insulative sheathing on exterior; Class I/II VR on inside.	Preferred: Class I/II insulative sheathing on exterior with Class III VR on inside. Alternative:[2] Class III insulative sheathing on exterior; Class I/II VR on inside.	Class I/II VR on inside; Insulative sheathing perm rating at least >1.
Desired Properties				
Rain Water Management/ Water Resistive Barrier (Note: Drainage plane shall be No. 15 asphalt layer compliant with ASTM D 226 Type 1 or other approved water resistive barrier.[3])	Install drainage plane to the exterior side of the framing/ insulation. Air space recommended with drainage plane (Lstiburek 2006).	Preferred: Using the insulative sheathing as a drainage plane (subject to demonstrated long-term durability of the sheathing or facing material) (Lstiburek 1999). Alternative: Install drainage plane to the exterior/interior of the insulative sheathing. Air space recommended with drainage plane.	Preferred: Using the insulative sheathing as a drainage plane (subject to demonstrated long-term durability of the sheathing or facing material). Alternative: Install drainage plane to the exterior/interior of the insulative sheathing. Air space recommended with drainage plane.	Preferred: Using the insulative sheathing as a drainage plane (subject to demonstrated long-term durability of the sheathing or facing material). Alternative: Install drainage plane to the exterior/interior of the insulative sheathing. Air space recommended with drainage plane.
Air Infiltration Resistance	Install a continuous air infiltration barrier on the exterior side of the framing/ insulation.	Install a continuous air infiltration barrier on the exterior/interior of the insulative sheathing.	Install a continuous air infiltration barrier on the exterior/interior of the insulative sheathing.	Install a continuous air infiltration barrier on the exterior/interior of the insulative sheathing.
Shear Resistance[4, 5] (non-wind zone areas)	Sheathing on the exterior side with structural strength of 210 plf minimum.	Sheathing on the exterior side with structural strength of 210 plf minimum.	Sheathing on the exterior side with structural strength of 210 plf minimum.	Sheathing on the exterior side with structural strength of 210 plf minimum.
Additional Specifications				
Cladding	Direct cladding	Preferred: Direct	Preferred: Direct	Preferred: Direct

Properties	**IECC Climate Zone 5**				**IECC Climate Zones 6, 7, and 8**			
	Reference Design		**Design 1**		**Design 2**		**Design 3**	
Attachment	attachment to structural sheathing.		cladding attachment through sheathing into the studs using extra-long fasteners (nails, screws etc.) that can be collated. Certain fasteners allow up to 4 in. of foam sheathing thickness. Alternative: Using furring or hat-channel over foam sheathing to support the siding.		cladding attachment through sheathing into the studs using extra-long fasteners (nails, screws etc.) that can be collated. Certain fasteners allow up to 4 in. of foam sheathing thickness. Alternative: Using furring or hat-channel over foam sheathing to support the siding.		cladding attachment through sheathing into the studs using extra-long fasteners (nails, screws etc.) that can be collated.	
Other Wall Characteristics								
Siding Material	Vinyl or fiber cement		Vinyl or fiber cement		Vinyl or fiber cement		Vinyl or fiber cement	
Nominal Insulation	R-21 HD batt insulation		R-13 batt insulation		R-13 batt insulation		R-21 HD batt insulation	
Framing	2 in. × 6 in.		2 in. × 4 in.		2 in. × 4 in.		2 in. × 6 in.	
Frame Spacing[6]	16 in. o.c.	24 in. o.c.	16 in. o.c.	24 in. o.c.	16 in. o.c.	24 in. o.c.	16 in. o.c.	24 in. o.c.
Wall U-Value	0.052	0.050	0.054	0.053	0.042	0.041	0.040	0.039

1. Class I VR: 0.1 perms or less (Vapor impermeable); Class II VR: ≤ 1.0 perms and > 0.1 perm (Vapor semi-impermeable); Class III VR: ≤ 10 perms and >n 1.0 perm (Vapor semi-permeable); Not a VR: > 10 perms (Vapor permeable).

2. Mandatory requirement for HUD code homes.

3. R703.2 Water-resistive barrier. International Residential Code 2012.

4. Using the gypsum board with a proper adhesive is expected to provide sufficient shear resistance in most areas, at least for homes built under the HUD standards. For modular homes, additional shear resistance may need to be provided by the materials placed outside of the framing, whether as a property of the insulative board (preferred) or through the use of an additional material, such as oriented strand board.

5. Focus on shear strength is a reflection of the industry need to build homes that stand up to racking during transportation.

6. Assumed framing fraction – 14.98% for studs at 16 in. o.c. and 12.15% for studs at 24 in. o.c.

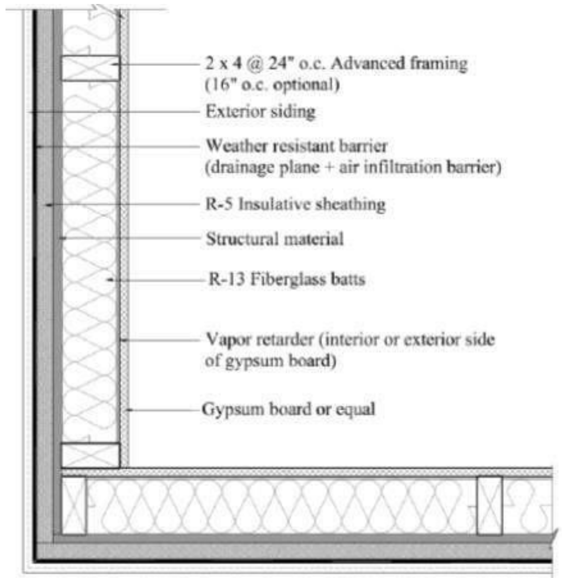
Source: The Levy Partnership, Inc.

Figure 1 through Figure 3 below were developed and provided to the participating insulation companies as typical wall sections with the thermal and vapor management properties meeting the IECC 2012 and International Residential Code (IRC) 2012 requirements, respectively. These figures were intended to be used as a base for developing variations on their current product offerings aimed at performing multiple functions, some of which were specific to the needs of factory homebuilders.

Figure 1 is a typical wall section of a stud wall with exterior insulation meeting the thermal requirements of IECC 2012 climate zone 5, based on the following heat flow targets:

- Prescriptive: R-20 or R-13+5 (wall insulation R-value).
- Whole wall performance: 0.057 (wall U-factor).

Figure 1: Stud Wall with Exterior Insulation, Design 1 (Climate Zone 5)



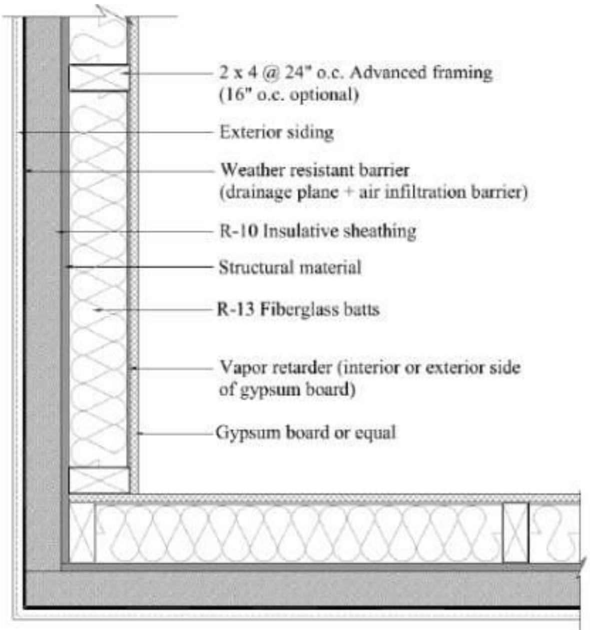
Source: The Levy Partnership, Inc.

Figure 2 and Figure 3 are typical wall sections of stud walls with exterior insulation meeting the thermal requirements of IECC 2012 climate zones 6, 7, and 8, based on the following thermal resistance targets:

- Prescriptive: R-20+5 or R-13+10 (wall insulation R-value).
- Whole wall performance: 0.048 (wall U-factor).

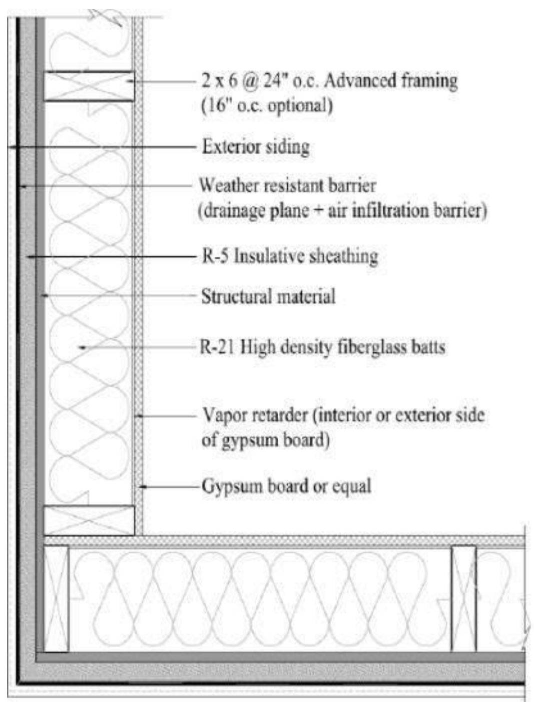
Figure 2 is a stud wall with 2” × 4” framing, R-13 cavity insulation and R-10 exterior insulation. Figure 3 is a similar wall section but with 2” × 6” framing and R-5 exterior insulation. Cavity insulation is R-20.

Figure 2: Stud Wall with Exterior Insulation, Design 2 (Climate Zones 6, 7, and 8)



Source: The Levy Partnership, Inc.

Figure 3: Stud Wall with Exterior Insulation, Design 3 (Climate Zones 6, 7, and 8)



Source: The Levy Partnership, Inc.

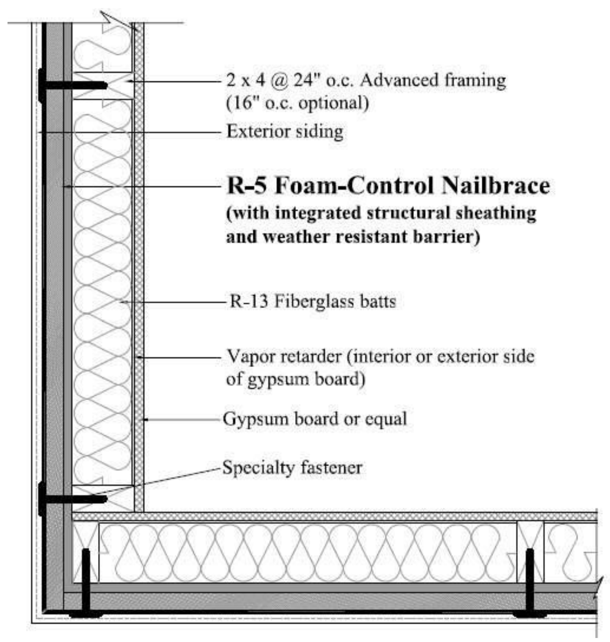
Advanced Wall Design Development

In conducting design development on the advanced wall design the technical team experimented with several extruded polystyrene (XPS) products that provide a minimum of R-5 for a 1” thickness. Participating insulation manufacturers were provided with the aforementioned wall performance specifications and asked to develop advanced wall solutions using their proprietary products. Various wall solutions were developed based on superior insulation products, these designs are described in detail in a report elsewhere. The following list includes the design concepts developed by these manufacturers:

AFM Corporation

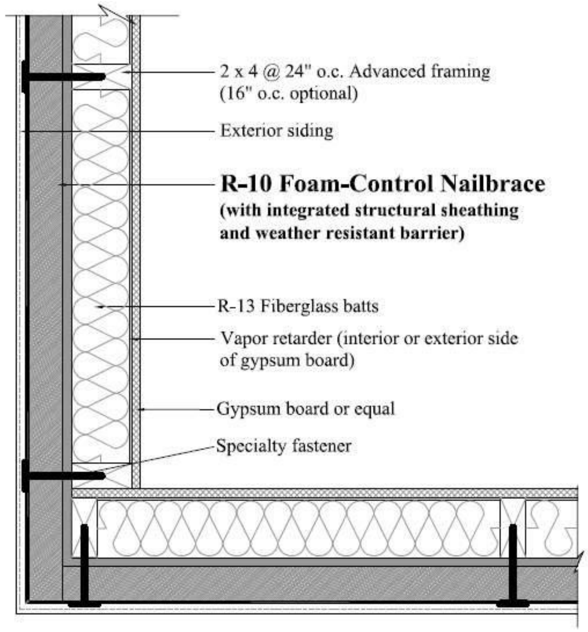
- Concept A: Stud walls with Foam-Control Nailbrace with integrated structural sheathing and weather resistant barrier (WRB).

Figure 4: Foam-Control Nailbrace Concept A, Design 1 (Climate Zone 5)



Source: The Levy Partnership, Inc.

Figure 5: Foam-Control Nailbrace Concept A, Design 2 (Climate Zones 6, 7, and 8)



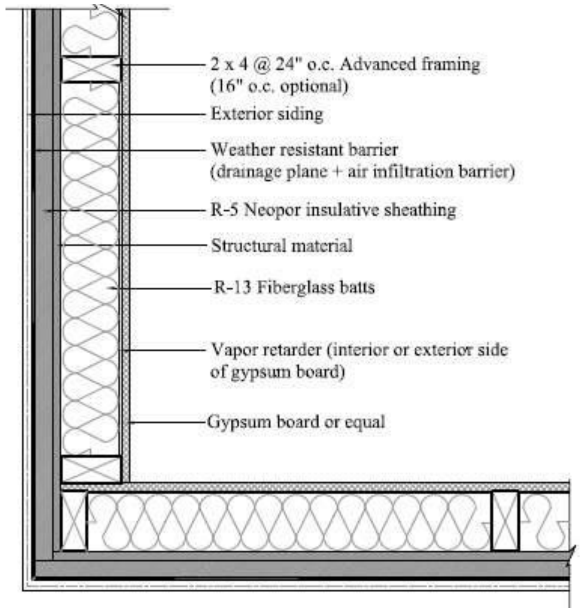
Source: The Levy Partnership, Inc.

BASF Corporation

BASF proposed four advanced wall designs incorporating insulation made from its NEOPOR (BASF 2011) rigid thermal insulation product. The four proposed design concepts are as follows:

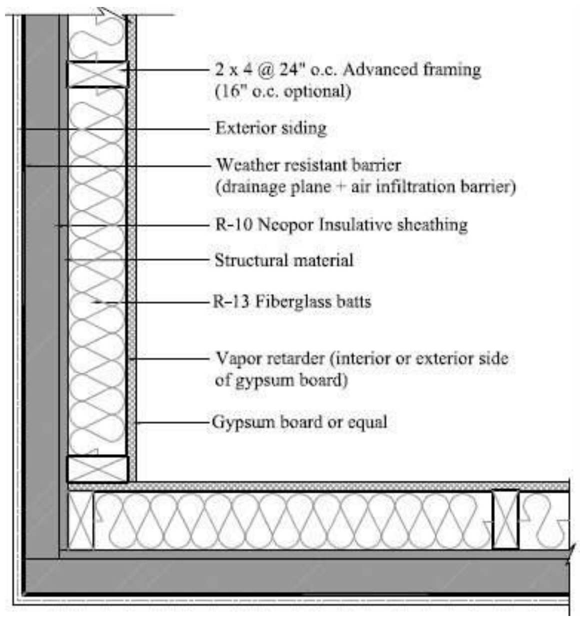
- Concept A: Stud walls with NEOPOR rigid thermal insulation
- Concept B: Stud walls with oriented strand board (OSB) laminated to NEOPOR rigid thermal insulation
- Concept C: Stud walls with poly-faced NEOPOR rigid thermal insulation
- Concept D: Stud walls with foil-faced NEOPOR rigid thermal insulation.

Figure 6: NEOPOR Concept A, Design 1 (Climate Zone 5)



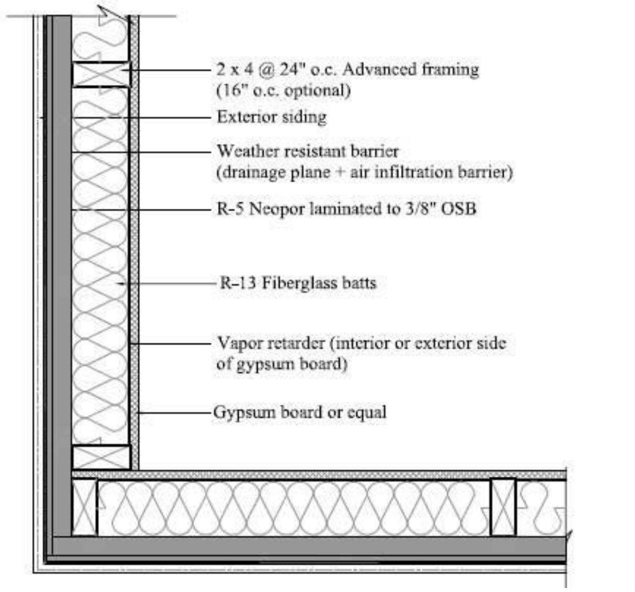
Source: The Levy Partnership, Inc.

Figure 7: NEOPOR Concept A, Design 2 (Climate Zones 6, 7, and 8)



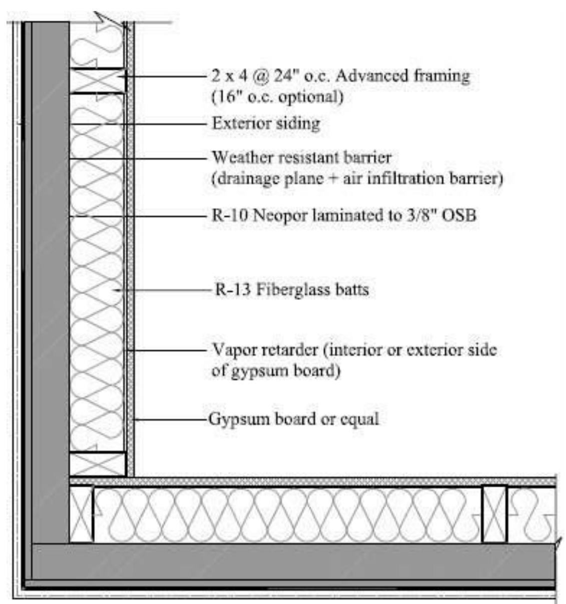
Source: The Levy Partnership, Inc.

Figure 8: NEOPOR Concept B, Design 1 (Climate Zone 5)



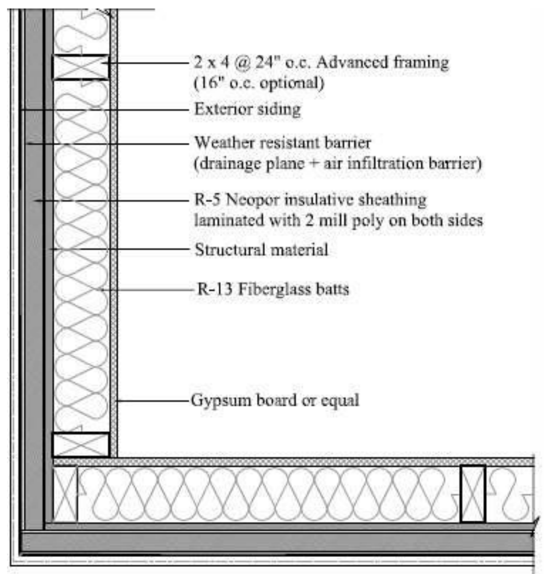
Source: The Levy Partnership, Inc.

Figure 9: NEOPOR Concept B, Design 2 (Climate Zones 6, 7, and 8)



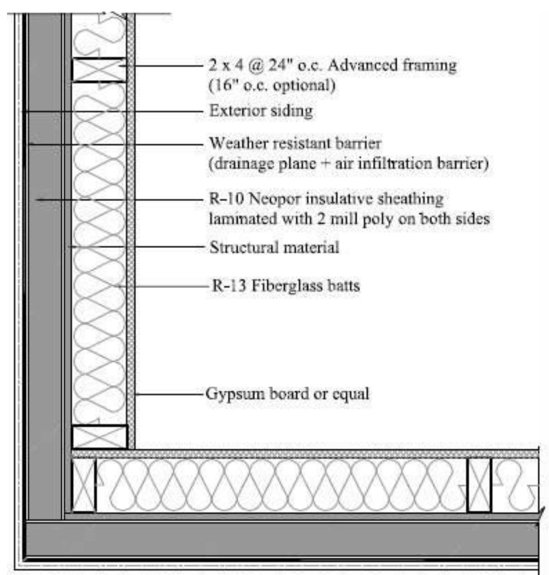
Source: The Levy Partnership, Inc.

Figure 10: NEOPOR Concept C, Design 1 (Climate Zone 5)



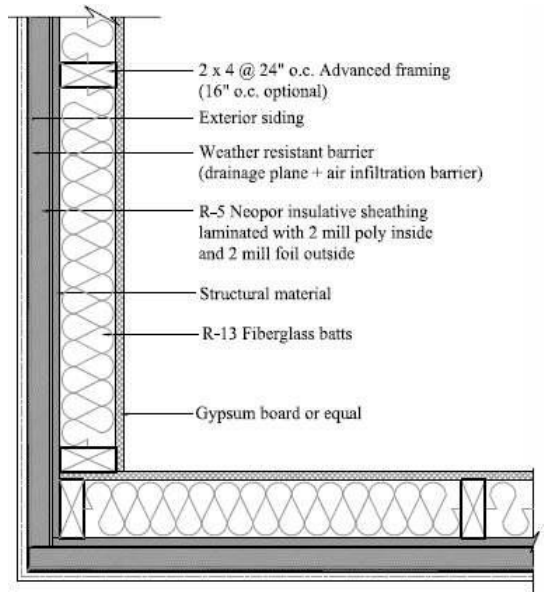
Source: The Levy Partnership, Inc.

Figure 11: NEOPOR Concept C, Design 2 (Climate Zones 6, 7, and 8)



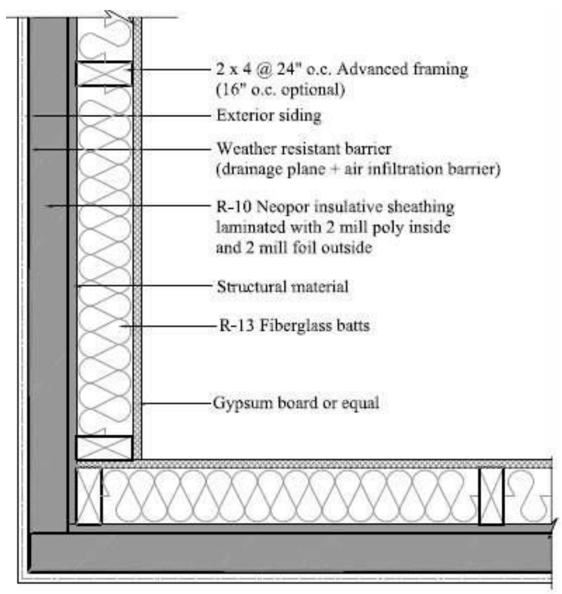
Source: The Levy Partnership, Inc.

Figure 12: NEOPOR Concept D, Design 1 (Climate Zone 5)



Source: The Levy Partnership, Inc.

Figure 13: NEOPOR Concept D, Design 2 (Climate Zones 6, 7, and 8)

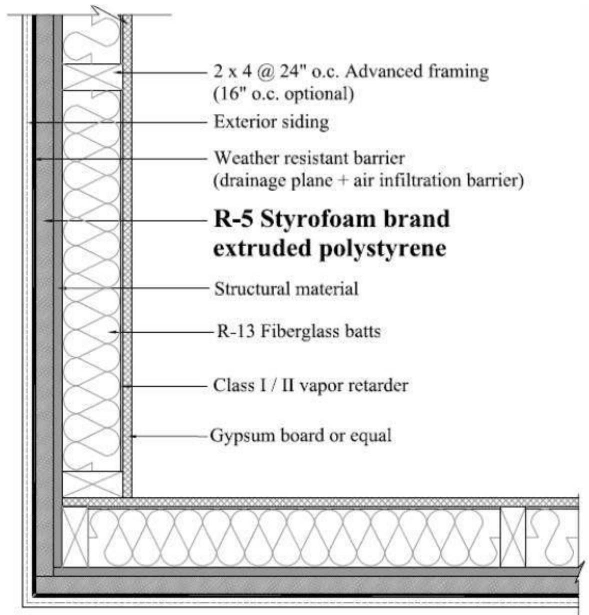


Source: The Levy Partnership, Inc.

The Dow Chemical Company

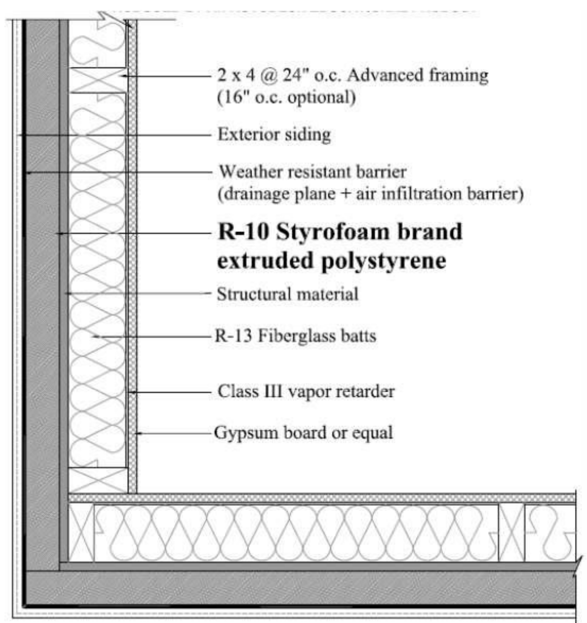
Dow proposed advanced wall designs incorporating its Styrofoam brand XPS insulation board. Figure 14 is a wall section with Styrofoam XPS designed to meet the 2012 IECC prescriptive code requirements for climate zone 5. Figure 15 shows the wall design meeting code requirements for climate zones 6, 7, and 8 with R-13 in the cavity and R-10 exterior insulation. A similar design was also developed for climates zones 6, 7, and 8 with R-21 in the cavity and R-5 exterior insulation.

Figure 14: Stud wall with Styrofoam, Design 1 (Climate Zone 5)



Source: The Levy Partnership, Inc.

Figure 15: Stud wall with Styrofoam, Design 2 (Climate Zones 6, 7, and 8)



Source: The Levy Partnership, Inc.

Johns Manville Corporation

JM proposed the following three wall designs incorporating polyisocyanurate insulation.

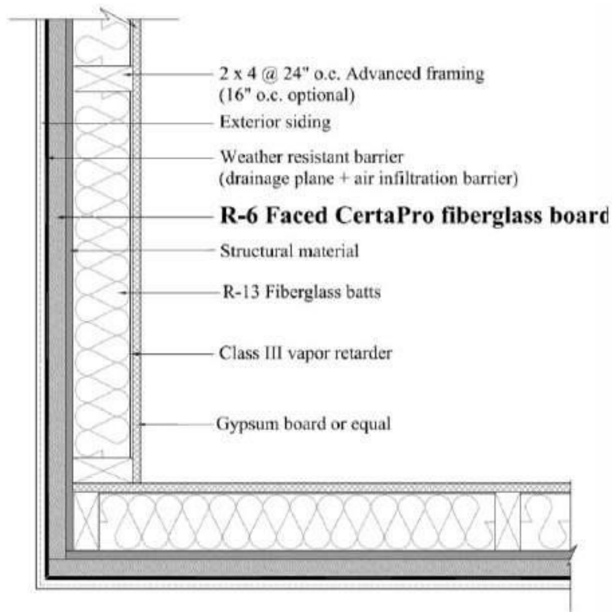
- Concept A: Stud walls with ValuTherm sheathing.

- Concept B: Stud walls with AP foil-faced sheathing.
- Concept C: Stud walls with structural insulated sheathing (SIS).

Saint-Gobain/CertainTeed

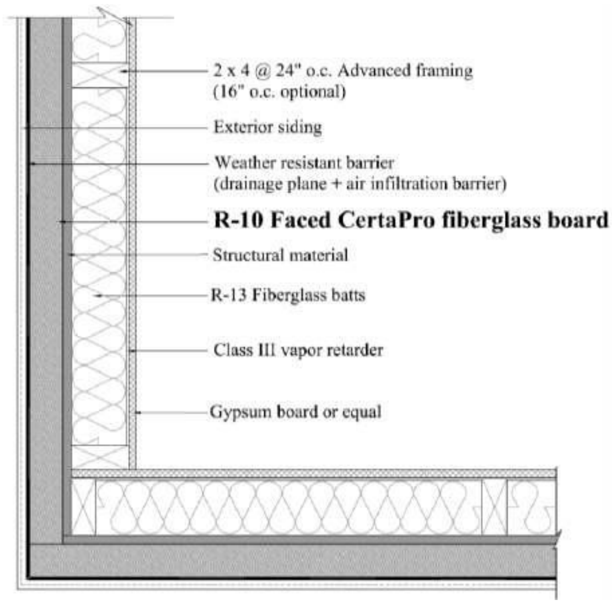
CertainTeed proposed an advanced wall solution incorporating their brand product CertaPro fiberglass insulative sheathing with an optional WRB facing. Figure 16 and Figure 17 show typical wall sections proposed for climate zones 5, 6, 7, and 8 in response to the specifications in Designs 1 and 2, respectively. A similar design was developed for climate zones 6, 7, and 8 meeting Design 3 requirements.

Figure 16: Stud Wall with Faced CertaPro, Design 1 (Climate Zone 5)



Source: The Levy Partnership, Inc.

Figure 17: Stud Wall with Faced CertaPro, Design 2 (Climate Zones 6, 7 and 8)



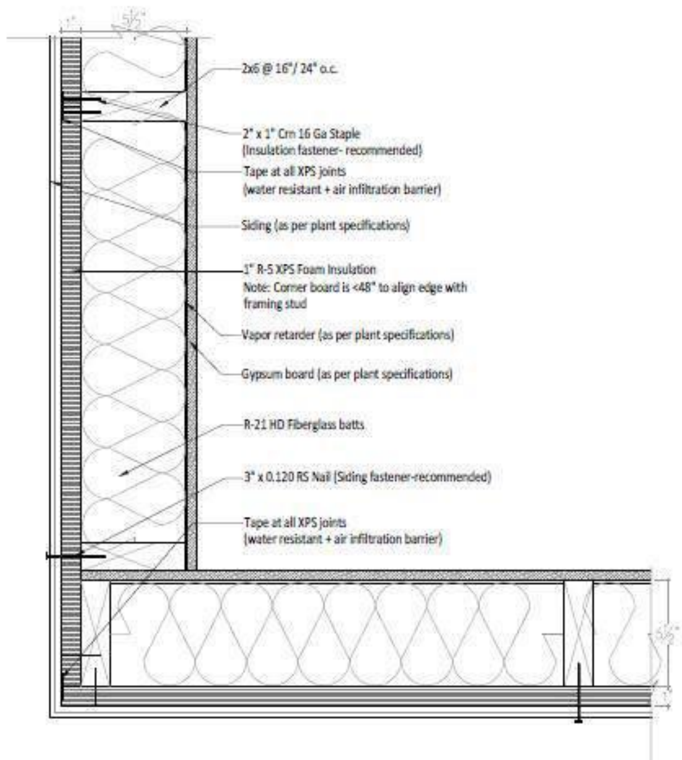
Source: The Levy Partnership, Inc.

Final Design Details

The following section focuses on the final design details developed as part of the advanced wall design solution. These drawings were developed with the intent of being incorporated state-wide with any commercially available insulation product that can be used to meet the needs for a CI in a factory building setting.

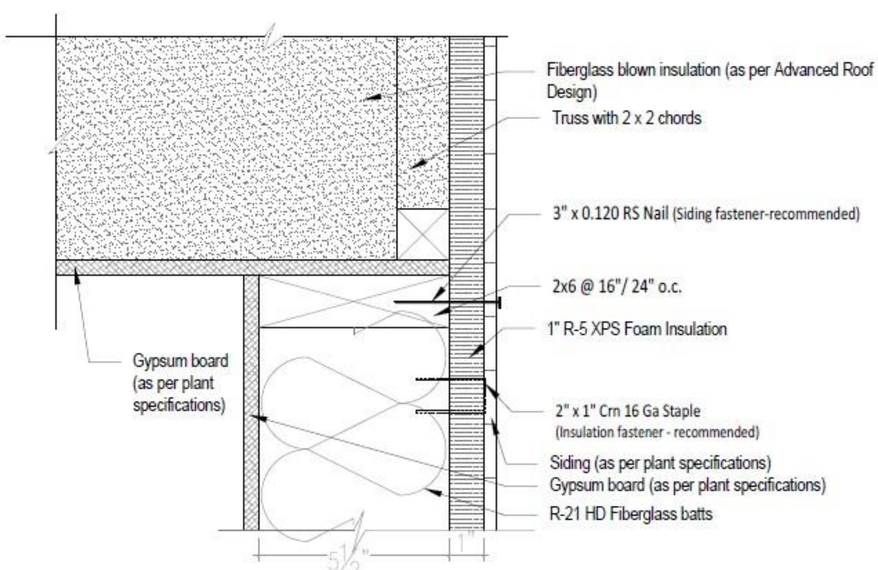
Figure 18 through Figure 22 are construction details incorporating the exterior CI to the wall assembly.

Figure 18: Plan View of Wall Detail



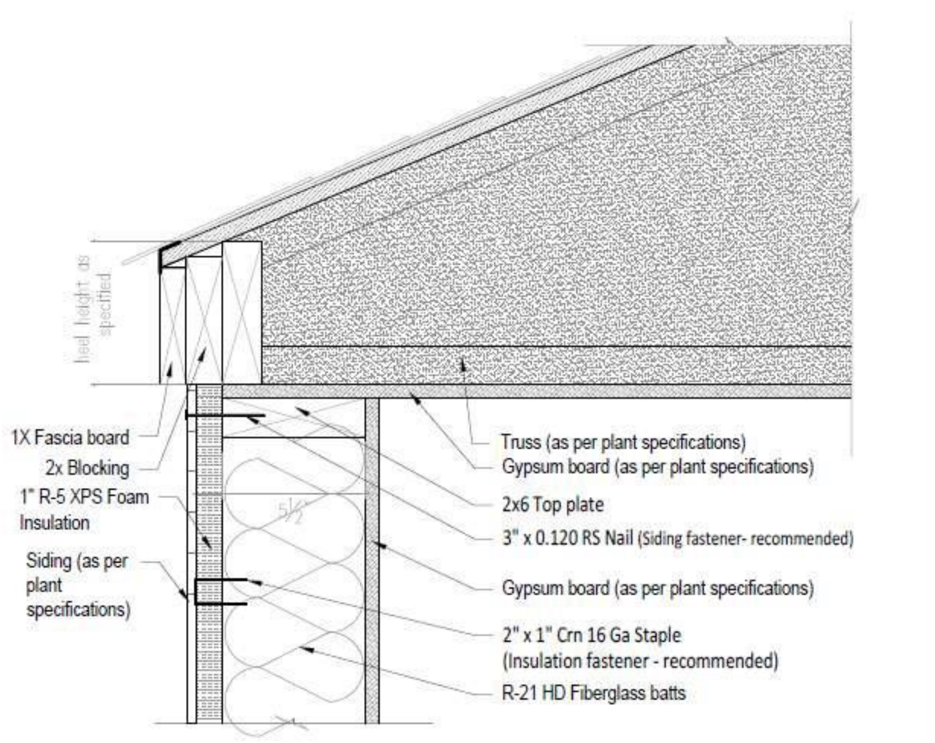
Source: The Levy Partnership, Inc.

Figure 19: Detail at Top Plate (Gable Wall Section)



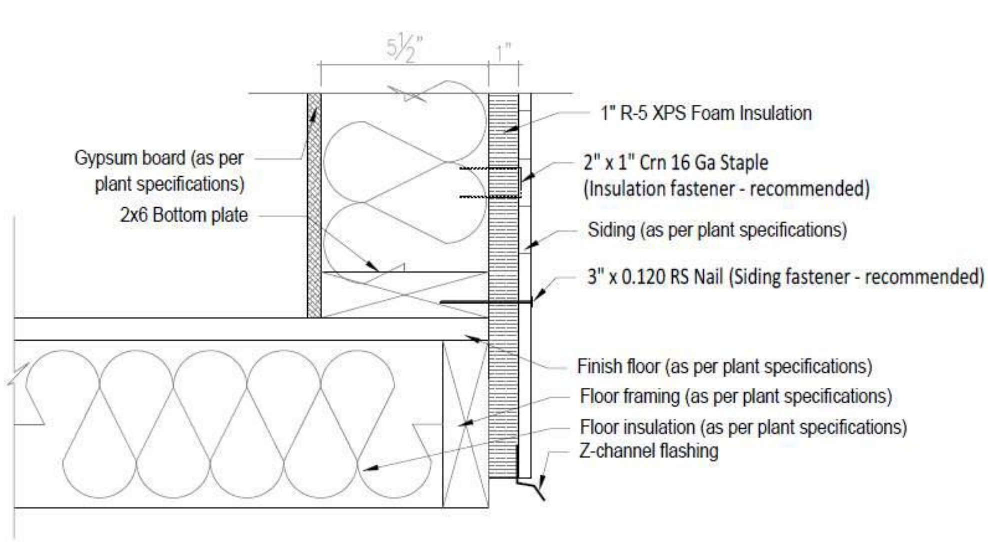
Source: The Levy Partnership, Inc

Figure 20: Detail at Roof Wall Connection (Side Wall Section)



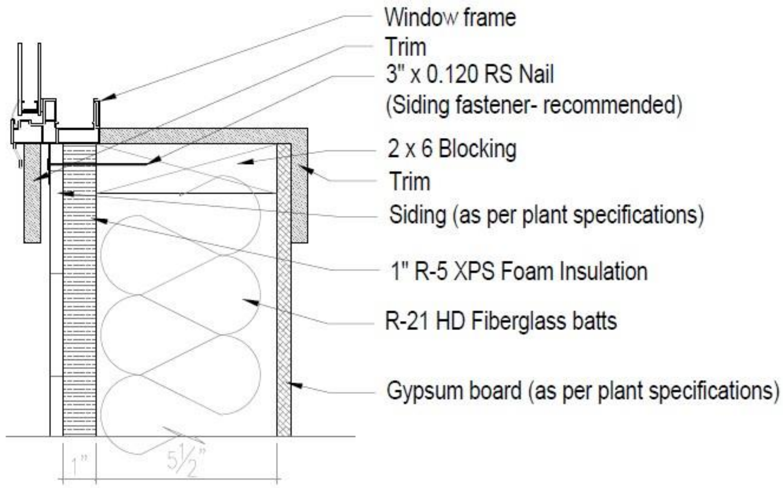
Source: The Levy Partnership, Inc

Figure 21: Detail at Foundation



Source: The Levy Partnership, Inc.

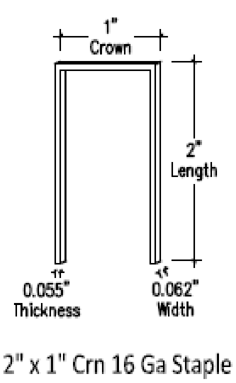
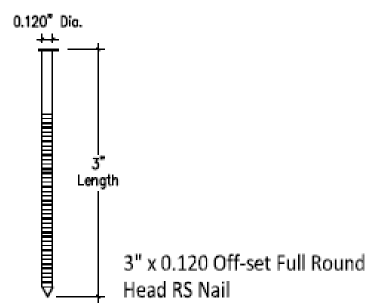
Figure 22: Detail at Window Sill



Source: The Levy Partnership, Inc.

Specifications on fasteners and tools required to attach CI to the framing and the cladding are shown in Table 2 and discussed below.

Table 2: Fastener Specifications

Item	Specification
Framing	2 in. × 4 in. @ 16 in. o.c.
Fasteners and tools	See below
Cladding attachment	LP Smart side 7/16 in. – Nail (3 in.) (www.lpcorp.com/smartside/panel/, www.lpcorp.com/resources/literature)
Furring or strapping	Not required
Insulation staple Senco 2” × 1” crown 16 gauge staple 	Siding nail Senco 3” × 0.120” RS Nail 

Source: The Levy Partnership, Inc.

Tools

- Staple gun: WC200 XP–16 gauge, 1” wide crown, 2” heavy wire stapler.
- Nailing gun: SN951XP-4” 34 clipped head framing nailer.

The fastening schedule for stapling the CI to the frame and nailing the siding in was specified as: one every 6” along the perimeter and one every 12” in the field.

Thermal and Cost Benefit Analysis

Typically, simulation tools such as BEopt are used to help differentiate among alternative measures for reducing energy use. Measures are assigned costs, their energy savings are estimated and then are ranked in terms of cost effectiveness. This approach allows different types of measures (impacting different end uses, with varying impacts on energy use and with different costs) to be readily compared and combined into cost-optimized whole building solutions. However, the team was operating within a different context for cost optimization where the end result is fixed (in this case, wall R-value to be achieved using insulative sheathing). The questions revert to:

- What is the least cost way to reach the specified R-value?
- What should the target cost be to achieve a designated economic return, such as payback or return on investment?

The first question was readily answered by comparing costs of alternatives: in this case, more than 50 options for using R-5 and R-10 insulative sheathing developed in partnership with six original equipment manufacturer (OEM) insulation suppliers. The task was simply to determine which option(s) is the least costly; material, labor, and related costs considered. The second question – what should be the cost to satisfy preset financial criteria – was more salient.

Different parties may have divergent views on what qualifies as cost effective. To begin to place bounds on the answer, an analysis was conducted for representative locations in IECC regions 5, 6, and 7 (all are in zone 3 of the HUD thermal standards). Energy savings was projected using BEopt and maximum measure costs were calculated that satisfy three economic metrics: simple pay back (7-year time horizon); return on investment (target 10 percent); and net zero cash flow (first year). The results are shown in Table 3.

For these three methods of measuring cost-benefit, the threshold maximum cost when adding insulative sheathing is \$0.80–\$2.54 (a huge range reflecting, in part, climate variations, energy costs, and differences in requirements by climate region, among other factors). To be deemed cost effective, the incremental cost of the measure will need to be equal to or below these values; that is, if the cost of the measure is higher than this range it can be broadly deemed not to be cost effective. (The three methods for conducting cost-benefit analysis are intended to be illustrative, not exhaustive. For example, using a life cycle cost optimization criterion would likely result in different allowable measure costs, as would modifying the assumptions used with any of the economic models.) The bottom line for the team is finding insulative sheathing solutions that will have a net cost to the consumer of less than $2.00/ft² for IECC region 5 designs and less than $3.00/ft² for homes in regions 6 and 7.

Table 3: Allowable Cost of Insulative Sheathing to Qualify as Cost-Effective

Location	IECC region	Energy savings ($/ft²/yr)	Maximum allowable cost ($/ft²)		
			Simple Payback (7 Year)	Return on Investment (10%)	Net Zero Cash Flow (year 1)
Cecilville, California	5	$0.114	$0.80	$1.14	$1.53
Markleeville, California	6	$0.157	$1.10	$1.57	$2.11
International Falls, Minnesota*	7	$0.189	$1.32	$1.89	$2.54
*Since no part of California falls under IECC climate zone 7 a representative location was selected elsewhere to assess the cost efficiency and energy savings in the three colder IECC climate zones.					

Source: The Levy Partnership, Inc.

At this stage in the analysis the actual anticipated costs of the proposed measures (materials, inventorying, added labor to install, amortization of special equipment, and so on) were not sufficiently detailed to be reliable. However, the allowable cost approach provided a valuable reference point for the team going forward. As noted earlier, these measures are likely to be mandated by code in the near future; that is, cost-benefit analysis results will be instructive but will not impact the decision by factory builders to construct walls with insulative sheathing.

The wall measures under investigation are part of a wider effort to move factory built homes to levels of energy use that are 50 percent less than current construction. The technical team with the industry focused attention on each envelope component sequentially (starting with walls) with the goal of developing and transitioning to market viability component designs predicated on cutting energy use by half. Table 4 suggests the extent to which the insulative sheathing solutions will impact energy use.

Table 4: Comparison of U-values

Description	Base Case	Design 1 IECC region 5	Design 2 IECC regions 6 and 7
Effective R-Value (Insulation Only)	11.4	17.0 (R-5 insulative sheathing)	22.2 (R-10 insulative sheathing)
Component U-Value (per BEopt)	0.877	0.059	0.045
Change in U-Value (%)	–	32%	49%

Source: The Levy Partnership, Inc.

Compared with current typical construction, future changes in the building code alone are expected to reduce wall-related thermal transmission energy use by about 32 percent (IECC region 5) and 49 percent (IECC regions 6 and 7), respectively. (The HUD standards [base case] currently have a single requirement for areas covered by IECC regions 5, 6, 7, and 8.) Moving practice to the R-10 insulative sheathing solution for homes in all of these regions (the 49 percent solution) is feasible provided the research can yield designs using R-10 insulative sheathing for a net cost of about \$3.00/ft^2, as discussed above. Achieving this cost target is a major goal of the next research phase.

Moisture Analysis

With the emphasis on providing greater insulation value on the exterior of the wall framing, the team considered how altering the thermal balance of the wall would change the dynamics of moisture flow and, consequently, the need for and location of a Class I or II vapor retarder (VR). Common practice in the northern, mainly heating-dominated climates is to place materials with low perm ratings on the interior of the wall. During the heating season, water vapor produced in the home is kept from entering the wall cavity where it might condense. However, many in the building science community contend that using a Class III VR on the interior is appropriate when applying insulative sheathing to the exterior of the wall. This view is codified in Section R702.7.1 of the 2012 IRC.[2,3]

In setting desired wall properties for the design development work, the team provided for three ways to approach moisture control: (1) using a Class I or II VR on the exterior of the wall; (2) applying a Class I or II material on the interior of the wall (as traditionally built); or (3) having no Class I or II VR anywhere in the wall. Preliminary WUFI® analysis was conducted on several of the designs.[4] Two cases illustrate the results.

Figure 23 shows a cross section of a wall with 2" of XPS insulation (blue bar). The wall, from exterior to interior, has exterior vinyl siding, XPS, OSB, framing with batt insulation, and gypsum board finished with two coats of latex paint. The insulation has a Class II VR rating; all other materials are rated Class III or are vapor permeable. The graph below charts the relative humidity (RH) and temperature at the inside surface of the OSB, the place in the wall experiencing the highest RH readings. As can be seen, RH, an indicator of the propensity of the wall to experience conditions that might be conducive to mold growth and condensation, peaks in the shoulder months. However, the conditions rarely exceed 95 percent RH for sustained periods, suggesting that this wall is unlikely to experience moisture-related failures.

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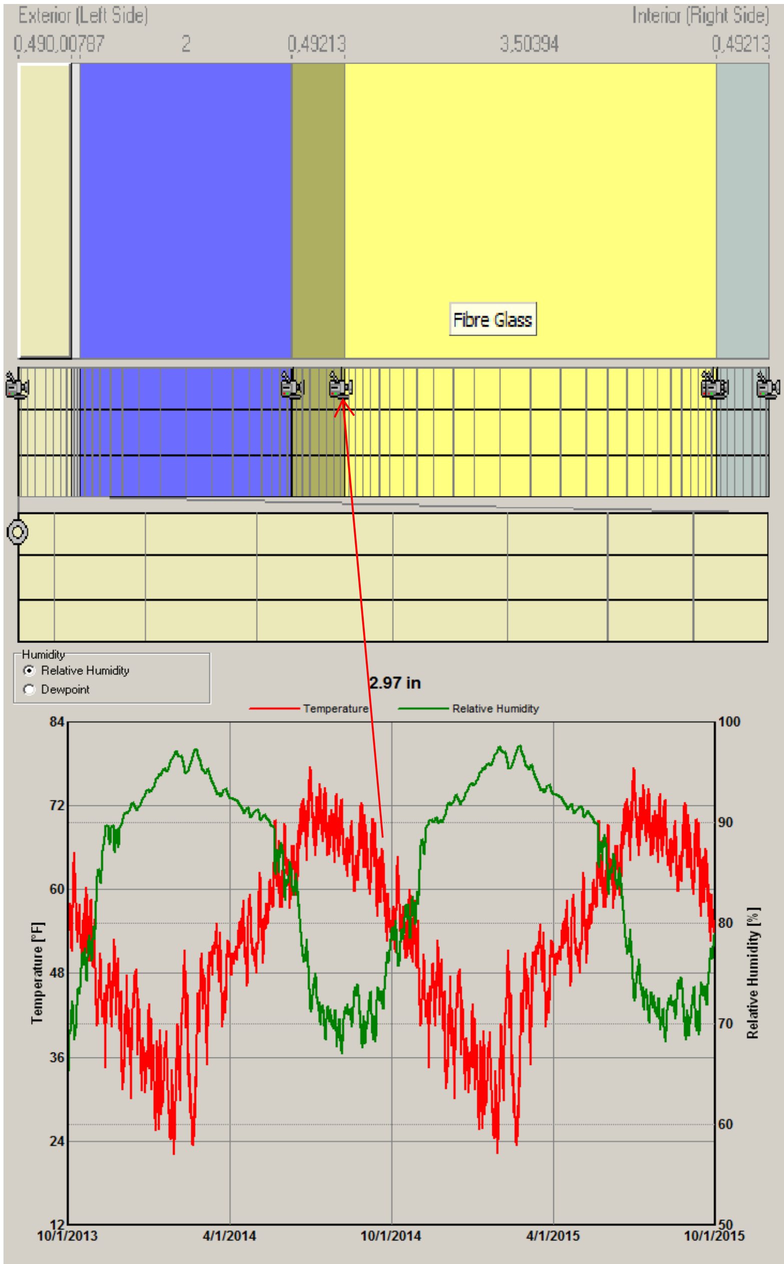
2 During a project Expert Meeting, Joe Lstiburek of Building Science Corporation discussed the testing and research conducted to support this approach and the genesis of the IRC requirement.

3 The moisture analysis considers vapor flow and ignores air transported moisture. Airflow and air leakage typically are much more significant to moisture transport than vapor diffusion.

4 WUFI® is a family of software products that allows realistic calculation of the transient coupled one- and two-dimensional heat and moisture transport in walls and other multi-layer building components exposed to natural weather (https://wufi.de/en/).

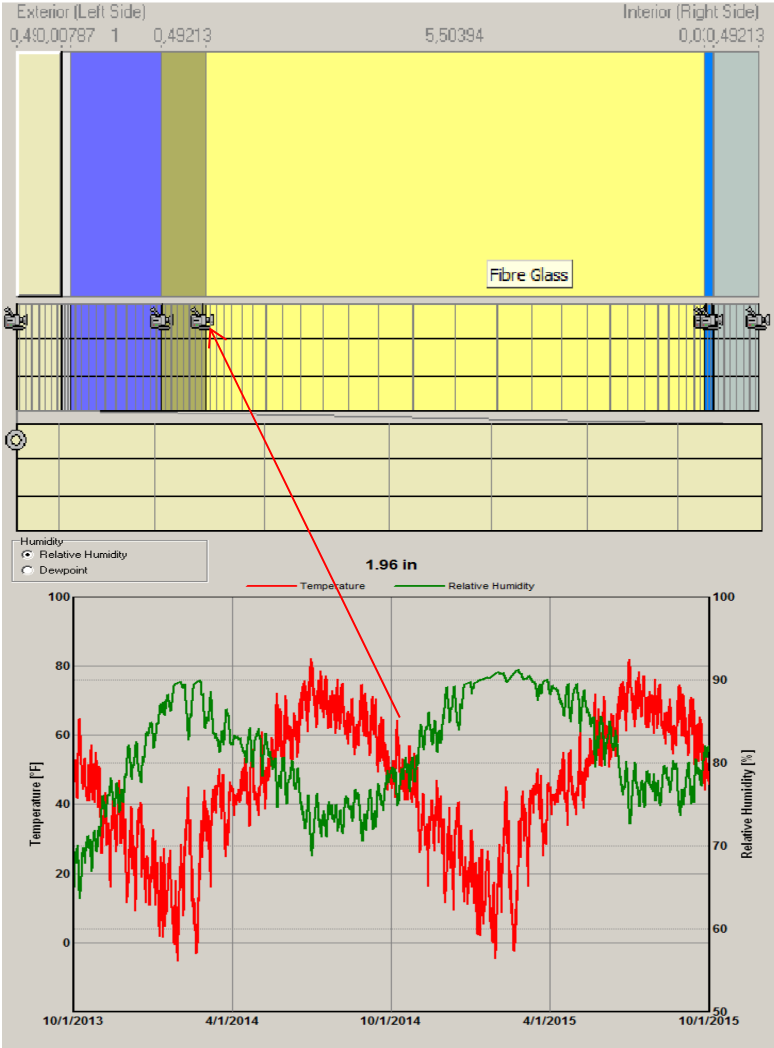
WUFI results for the 6" frame wall with R-5 insulative sheathing show a similar pattern with lower RH values (see Figure 24). This wall uses the same materials, although a Class II VR is applied between the framing and gypsum board. It is likely that removing the VR would elevate RH levels but not to a degree that would cause concern. This configuration will be explored further in subsequent phases of the research.

Figure 23: WUFI Results for Wall with R-10 (2" XPS) Insulation in International Falls



Source: The Levy Partnership, Inc.

Figure 24: WUFI Results for Wall with R-5 (1" XPS) Insulation in International Falls



Source: The Levy Partnership, Inc.

Code Compliance

RADCO performed research to ensure the proposed wall design was able to meet the requirements within the Manufactured Home Construction and Safety Standards, specifically related to the use of XPS continuous insulation. The wall design was reviewed for code compliance and passed without issues. The full report from RADCO is available in Appendix A.

Component Prototyping

Component prototyping of stud walls with exterior continuous insulation (CI) was conducted on October 2, 2013 in association with partner manufacturing plant, Karsten Homes, Inc. (Sacramento, California). Karsten Homes is a subsidiary of Clayton Manufactured Homes. The exterior continuous insulation board tested was FOAMULAR® 250 XPS, an XPS product manufactured by Owens Corning.

Figure 25: Component Prototype Wall Build, Karsten Homes, Sacramento, California

Source: Emanuel Levy

Test Plan

Purpose: Identify and resolve any issues associated with using foam insulating sheathing board (FOAMULAR® 250 XPS insulation) on the exterior of stud walls. The prototype test unit was 2' 8" by 10' 0", with 2"x 4" stud framing placed 16" on center. 1" of continuous extruded polystyrene (XPS) insulation was placed outboard of the studs, in addition to the fiberglass batt insulation present in the plants baseline builds. The unit was sided with 7/16" engineered wood panel board. Table 5 shows the physical properties of the insulation used.

The framing panel was assessed based on the following factors: assembly, production, installation of doors and windows, fastening techniques and other related issues.

Test Results, Analysis and Recommendations

The purpose of the wall component mock-up was to consider issues that will arise in the plant when using the CI in factory production. The mock-up process simulated elements of the construction process identifying steps in the material and product assembly (for example, fastening, door/window framing, and so on) that had the potential to slow production or adversely impact quality.

The discussion that follows highlights the main findings of the mock-up simulation.

Table 5: Physical Properties of XPS Insulation Used at Karsten Homes

Item	Property
Insulation brand name	FOAMULAR® 250 XPS
Insulation type	Extruded polystyrene or XPS
Product thick. @R-5	1”
Perm rating @1”	1.1
Compressive strength	25 psi
Integrated water and air barrier	Yes, with JointSealR™ tape
Shear resistance	Not significant
Strengths	• Can be cut with a saw, hot wire or scored and snapped • Zero ozone depletion potential indicating negligible degradation to the ozone layer • Limited Lifetime Warranty maintains at least 90% of its R-value over the lifetime of the product and covers all ASTM C578 properties • Contains minimum 20% recycled content • The only XPS foam to be GreenGuard Certified • The only XPS foam with certified recycled content – certified by Scientific Certification Systems (SCS) to contain a minimum 20% recycled content
Limitations	• Non-structural
Weight	• Min. 1.6 pcf
Available panel sizes	• 96” x 16”or 24” or 48” • 108” x 48”

Source: The Levy Partnership, Inc

Lessons from the Prototype Demonstration Build

The construction of the prototype wall panel helped acquaint key production staff with the use of CI and expose and begin to resolve issues that otherwise might slow production. Two major concerns arose during the prototyping with the potential to negatively impact plant flow: the use of tape at the panel seams and the method of cutting window and door openings.

- Taping of seams: Taping of the insulation seams during mock-up was a slow, arduous process and the team feared that this process would significantly slow production. Application of the tape required practice and discussion ensued with regard to the utility of commercially-available taping tools. The team considered eliminating the taping but was concerned that other sealing techniques would not provide a sufficiently weather-tight barrier. However, during prototyping, the plant staff quickly adjusted to the taping process, and this concern abated somewhat although a better taping method is needed.

Figure 26: Taping of Seams

Source: The Levy Partnership, Inc.

- Cutting openings: After several unsuccessful attempts to cut openings after the insulation and siding was applied, the team concluded that a fast and accurate cutting of openings required a routing tool not available for the prototyping. As an interim measure, the plant quality control manager used a hand-held circular saw to cut the openings. This proved somewhat imprecise but adequate for the prototype. This interim solution is not an option going forward. Precise and clean routing of the insulation and siding will require locating the proper router bit with sufficient length to penetrate the materials and rest on the framing as a guide.

Figure 27: Hand-held Circular Saw was used to Rout Openings

Source: The Levy Partnership, Inc.

Below are findings from the wall panel mock-up demonstration in response to the research questions identified in the component test plan.

Assembly/Production

- Are there issues with handling the CI material, such as, weight, dimensional stability, ease of positioning, tacking, and so on?
    - *Finding:* For plant staff used to moving board materials, such as OSB, CI is relatively easy to handle in terms of the weight, dimensional stability, ease of positioning and tacking.
- What are the best methods of cutting openings in CI only or CI w/siding?
    - *Finding:* While not demonstrated, the consensus view is that the best method of cutting CI is by a router with a sufficiently long bit to cut through the siding and the CI in a single pass using the framing as a guide.
- What are the best methods for minimizing waste?
    - *Finding:* Pre-cutting pieces and using smaller left-over pieces at the gable end would minimize waste.
- Should window/door openings be cut out of the CI after installation on the wall or should smaller, pre-cut pieces be used that would eliminate waste but require more custom cutting?
    - *Finding:* Cutting the door and window openings following the sheathing process was faster and less prone to quality issues.
- What are the best methods of consistently hitting studs with fasteners?
    - *Finding:* The production team suggests that the CI manufacturer print lines on the CI material that correspond to the stud spacing.
- What are the best methods of applying JointSealR™ tapes?
    - *Finding:* JointSealR™ tape is applied at all seams of the FOAMULAR® 250 XPS panels including corners. The best method of applying the tape is to have one worker position and hold the tape at one end of the seam while the other rolls it over the length of the seam. At the corners, it was decided that the best method would be to tape it on the side of the panel joint with the edge of the tape flushed with the corner edge. Having the tape wrap over to the other side was deemed unnecessary while requiring extra labor.

Fasteners

- Is the fastening schedule reasonable?

- *Finding: The* fastening schedule was deemed adequate by the insulation and siding manufacturer representatives and the plant staff.

- Do the specified siding fasteners ensure required penetration into the framing?
    - *Finding:* Yes, 3” long nails were specified to attach the 7/16” thick siding to the studs through the 1” of CI. The manufacturer of the panel siding (SmartSide by Louisiana Pacific) requires 1.5” of fastener penetration into the framing member.

Figure 28: Fasteners: Nails and Staples

Source: The Levy Partnership, Inc.

- Does the nailing gun ensure adequate and consistent air pressure to avoid dimpling during fastening and nail-popping during transportation and wall build?
    - *Finding:* Yes, the nailing gun pressure could be accurately adjusted to ensure adequate and consistent air pressure to avoid nail-popping and dimpling.
- Does the nailing gun require pressure adjustment on the line for different products, a step that might slow production?
    - *Finding:* While the nailing gun did not require pressure adjustment on the line, every siding nail type required the hammer to be reset. This was not considered a significant issue.

Door/Window Construction Assessment

- What are the best methods of installing windows?
    - *Finding:* Cutting window openings with a router with longer bit and installing the frame on the wall assembly followed by attaching the siding to the frame is likely to

be the best and most efficient method of installing windows. This will be investigated in latter stages of the work.

- With the windows resting partly on the insulation, is additional structural support required?
    - *Finding: According* to the window supplier, the structural rating of the CI (25 psi) provides sufficient support. While anecdotal, it should be noted that no window displacement or movement was observed after the homes were transported to the building site.
- What is the best approach for extending the depth door and window jambs to provide a flush surface for the interior trim?
    - *Finding: For* the Karsten plant, the best approach was to insert blocking that extended the jamb depth and provided a flush surface for the interior trim.

Evaluation

In general, the use of CI (in this case, Owens Corning's FOAMULAR® 250 XPS insulation board and related products) offered a solution that is fairly well-resolved with regard to construction detailing. The foam panels provide a continuous insulation layer that is durable, virtually eliminates thermal bridging, and can be installed in the plant with little training. Application of the tape to the joints enabled the material to also serve as an air and water resistive barrier, providing potential cost savings by eliminating the need for a separate material to serve this function. The relative high density and compression strength of the foam appears to be sufficient to allow the window to bear partially or entirely on the foam, enabling the use of fairly simple window and door framing details.

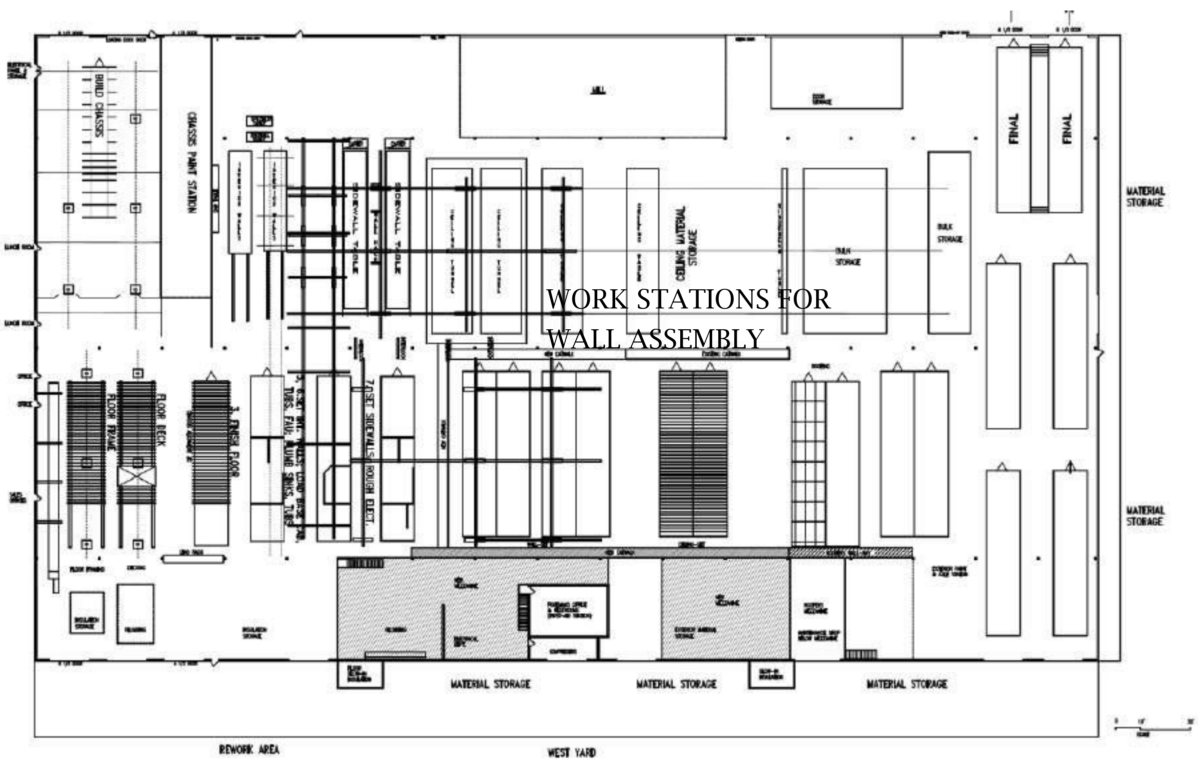
Manufacturing Process Analysis

The manufacturing process was analyzed to develop a manufacturing strategy for "stud walls with continuous exterior insulation" that, by streamlining overall production, substantially reduces total cost. Karsten Homes, a manufactured home building plant in Sacramento, California, hosted the component demonstration build and full-scale whole house prototyping of the selected wall design, and also served as the model for analyzing the production process. This section addresses and analyzes the construction process of a test home with continuous foam insulation on the exterior walls. To provide context, the baseline (current) process was also characterized. That allowed needed process changes to be identified and their impacts on production performance to be estimated.

Baseline Process

The baseline (current) manufacturing process at Karsten Homes was observed on October 2, 2013. The observation focused on activities that could be affected by the use of rigid foam insulation on the exterior walls. This includes all activities performed on the exterior of the walls: installation of weather resistant barrier, sheathing and/or siding, flashing, windows, doors, trim and eave soffits; cutting out openings for exterior lights and receptacles; and painting the siding. These activities are performed in workstations 12 – 17 of the production line. The line is currently producing three floors per day, operating on a 2.5 hour line cycle time. The exterior wall crew responsible for these activities consists of five workers. The crew typically divides into two teams of two workmen each, with each team performing all activities on every other floor as it moves through workstations 12 and 13. On an average, it takes each team five hours (two line cycles) to complete all exterior wall work on a given floor. The fifth member of the crew performs single-worker tasks for both teams, including painting, if needed. A separate crew of utility workers performs specialty tasks associated with more complex, custom designs. For example, the utility crew assists a team when their floor requires both exterior sheathing and siding, an infrequent design option at Karsten.

Figure 29: Karsten Plant Layout



Source: The Levy Partnership, Inc.

Description of activities

The baseline activities affected most by the use of rigid foam insulation are the installation of house wrap, siding and flashing, and the cutting out of openings in the siding for windows and doors.

The house wrap is installed in two bands, by a two-worker team. First, a three foot wide lower band is installed around the base of the wall. Then a wider, overlapping upper band is installed to the eave. When installing the upper band, one worker works on a rolling scaffold, while the second works below on the factory floor. House wrap is unrolled, cut-to-size, positioned, tacked, and then permanently attached using a staple gun.

Siding is installed by a two-worker team using the following process:

- Retrieve sheets of siding (4' x 9') from a staging cart located near the end wall and stage against the walls.
- Install a ledger board at the base of one end of the wall to place the first sheet.
- Position the first sheet on the ledger board, tack and then permanently attach using a nail gun and finally reset every nail by a hammer. Note that the bottom edge of the sheet is not attached to allow flashing to be installed underneath at a later time. One worker works on a rolling scaffold, while the second works below on the factory floor.
- Remove the ledger board after the first sheet is attached.
- Follow the above steps to install the remaining sheets on the wall, one sheet at a time. Move the rolling scaffold and air hoses after every two sheets.
- Measure the width needed for the last sheet, cut the sheet to size on the table, saw and install.

Siding may be installed differently on the end walls:

- One worker may perform the activity.
- A single worker may use a ladder instead of a rolling scaffold, since it is easier to handle. It is also difficult to use a rolling scaffold to work on the end wall at the tongue end of the floor.
- Siding at both ends of an end wall may need to be cut-to-size to allow panel edges to fall on a stud.
- An additional (gable) band of siding is required on the end wall. A full height lower band of siding is installed first. Then measurements are taken at the gable, sheets are cut-to-size and installed.

Flashing is installed by a single worker using the following process:

- Retrieve 10' long sections of metal flashing from the staging area and stage on the factory floor along the wall.
- Position each section of flashing under the bottom of the siding and tack through the siding using a nail gun.
- Complete attachment of siding and flashing using a nail gun.
- Measure for the last section of flashing at the end of the wall, trim to size and attach.

Openings for windows and doors are cut out of the siding by a single worker using the following process:

- Locate openings from the interior by using a hammer to penetrate the siding near the center of each opening.

- While standing on a rolling scaffold on the exterior, use a router to cut out each opening, using the framing as a guide.
- Remove cut-outs from the area and discard.
- Attach siding to the frame around the opening with a nail gun.

Analysis of Observed Performance

Exterior wall activities were performed safely. Personal safety equipment (safety glasses, hard hat) was worn by workers at all times. Power tools (staple/nail guns, router, table saw) were used responsibly and professionally. Rolling scaffolds provided safe access to the upper wall. Workers took shelter during overhead movement of material (shingles) and equipment (catwalks).

Activities were performed with a high degree of precision/quality. No discrepancies or rework were observed.

Activities were performed efficiently and within the required cycle time. The crew appeared well-trained and maintained a brisk, yet sustainable work pace. There was little observed idle time. The organization of the crew into small, multi-worker teams helped ensure pacing with little lost time. Tools and equipment were job-appropriate and located near their point of use. Siding was staged on a cart near the point of use.

Process time estimates for select activities are shown in Table 6. Estimates include all work on a 56' x 14' floor, except where otherwise noted. Note that estimates are based on very limited observation and, therefore, are only rough approximations.

Table 6: Process Time Estimates for Select Baseline Activities

Activity	Clock time (mins.)	No. of workers	Labor hrs.
Install house wrap	14	2	0.5
Install siding on side wall	39	2	1.3
Install siding on one end wall (excluding gable)	33	1	0.5
Install flashing	48	1	0.8
Cut out one opening	5	1	0.1

Source: The Levy Partnership, Inc.

No idle time or delays in line movement were observed due to off-standard conditions (such as accidents, tool/equipment malfunctions, defects/rework, material unavailability, poor work pace, and so on). The layout of the area was logical and efficient.

Baseline production performance was, in general, very good. However, some possible opportunities for improvement were noted:

- Can a single band of house wrap be used on the sidewalls (instead of two)?

- It is difficult for a worker installing wrap and siding on a scaffold to work under a catwalk. Can the catwalk be raised or moved while performing these activities?
- Is there an alternative to resetting every siding nail using a hammer?
- Is there an alternative to cutting siding on both ends of an end wall to size?
- Is it possible to improve flow by reducing unnecessary interruptions? Interruptions in the area are frequent. Productivity is lost each time a worker is interrupted from his/her task. Time is lost beyond the legitimate interruption – it takes a while to get back on task, particularly for a single worker not working as part of a team. Interruptions observed included cutting siding to size, stopping for overhead material handling, moving to provide aisle access on the back end and assisting another worker.
- Can a waste receptacle be located in the area for cut-outs?

Test Process

The process for installing rigid foam insulation on the exterior walls of the test home was observed on October 3, 2013. In planning for the test, the use of rigid foam was assumed to be well within the capabilities of the Karsten production system, which routinely produces highly customized homes. The flexibility of the production system – its ability to readily accommodate extra work - is supported by two key mechanisms: (1) a well-staffed, highly experienced utility crew; and, (2) ample workstations. For example, Karsten typically produces homes with structural siding, which require no sheathing. The exterior wall crew wraps the walls and installs siding in workstations 12 and 13 (see Figure 33). However, some Karsten designs require both sheathing and siding. For these atypical homes, the utility crew performs the extra work (installs sheathing). The two crews have workstations 12 – 17 to perform all activities on the exterior walls. In planning for the test, it was assumed that the rigid foam could be successfully installed like sheathing on the Karsten line. The process test was observed to verify this assumption, document the extra work and other production challenges associated with the test home design, and identify design and process changes that might facilitate production of the new design.

Description of Activities

This section describes the changes observed in the baseline Karsten production process. Changes were observed in the following activities:

- Install house wrap (not required for the test home).
- Install additional 2” x 6” lumber along the eave – added as backer for trim detail.
- Pre-cut 6” strips of rigid foam – needed to cover full height of the side wall.
- Install rigid foam – added layer of material.
- Pre-cut siding – reduce height to 102”.

- Install siding, flashing, windows, doors and trim – install over and fasten through rigid foam; door trim requires different details.

- Cut out openings in the siding for windows and doors – use hand-held circular saw instead of router.

No house wrap was required in the test home. Instead, the rigid foam, sealed at the joints with specialty tape, served as a weather barrier.

The basic design of the test home required no eave overhang. This design decision was not related to the use of rigid foam. However, the use of rigid foam did require the use of additional 2” x 6” lumber installed along the eave to provide backing for the eave trim above the rigid foam and siding. The lumber was installed by one worker after roof set and before installation of the rigid foam. Working on a ladder, the worker positioned each 2” x 6”, tacked it in place and completed attachment using a nail gun. A hand-held circular saw was used to cut the 2” x 6” at the end of the wall to size.

Use of 8’ long sheets of rigid foam on the 102” high wall required an additional 6” wide band of rigid foam along the base of the side wall. These 6” strips of rigid foam were pre-cut in two steps: (1) retrieve sheets of rigid foam from a pallet in the staging area; and, (2) cut each sheet into 6” strips using the table saw.

Two teams, varying in size from one to four workers, simultaneously installed the rigid foam on the two floors of the test home. The following process was used for the side walls:

- Retrieve full size rigid foam sheets and pre-cut rigid foam strips from the staging area and stage against the wall.

- Position a full size rigid foam sheet at the top of the wall (below the 2” x 6” lumber) and tack using a staple gun. When positioning at the end of the wall, be sure that the sheet is flushed to the end of the wall framing, allowing a tight foam seal around the corner. Complete attachment using a staple gun. To perform this and the remaining tasks, one to two workers work on a rolling scaffold while one to two workers work below on the factory floor.

- Position a pre-cut rigid foam strip below the full size sheet and tack using a staple gun. Complete attachment using a staple gun.

- Tape the horizontal seam between the lower and upper bands of rigid foam. Tape all vertical seams along the side and end walls and corner joints.

- Caulk between the upper band of rigid foam and the 2” x 6” lumber at the eave.

- Cut out the rigid foam from window and door openings using a router. Use the framing as a guide to attach the rigid foam insulation around each opening with the help of a staple gun.

- Install the remaining rigid foam along the length of the wall using the same procedure. Move the rolling scaffold, air lines and electric cord after the installation of every two sheets. Shortly after the test started, the workers discovered that the width of the rigid foam sheets was greater than 48" (actually it varied from 48 ¼" to 48 ½"). Consequently, after a few rigid foam sheets were installed, the edges no longer fell on a stud. A couple of workarounds were used to compensate for the panel production error. Typically on every second or third sheet, either a backer stud was added or the width of the rigid foam sheet was trimmed.

- Measure the width needed for the last pieces of foam at the end of the wall, cut the pieces to size on the table saw and install.

Figure 30: Installing and Tacking Foam Boards

Source: The Levy Partnership, Inc.

Figure 31: Trimming a FOAMULAR® 250 XPS Board

Source: The Levy Partnership, Inc.

Rigid foam was installed differently on the end walls.

- One to two workers perform the activity. Higher work is performed on a ladder or rolling scaffold.
- Full height sheets of rigid foam are installed across the bottom of the wall. Then measurements are taken for the gable, and the foam is cut to size on the table saw, carried to the line and installed.
- The material is cut to size on both ends of the wall. The foam board must overhang each end by 1” to provide a tight foam seal around each corner. The other vertical edge must land on a stud.

Figure 32: Installing Foam Board at the Gable

Source: The Levy Partnership, Inc.

The 9’ long siding was pre-cut to 102” to accommodate the eave detail on the side walls. Siding was cut to size using a hand-held circular saw directly on the staging cart.

Longer fasteners were required to install siding, flashing, windows, doors and trim through the siding and rigid foam and into the frame. This change did not noticeably affect the process.

Openings on siding for window-doors were cut by a single worker using the following process:

- Locate openings from the interior by using a nail to penetrate the siding at each corner of each opening.
- While standing on a ladder on the exterior, use a straight edge to outline the opening, using the nail holes as a guide.
- Use a hand-held circular saw to cut out each opening.
- Remove cut-outs from the area and discard.
- Attach siding to the stud frame around the opening with a nail gun.

Figure 33: Siding Installation

Source: The Levy Partnership, Inc.

Figure 34: Cutting Window Opening with Circular Saw

Source: The Levy Partnership, Inc.

Analysis of Observed Performance

Rigid foam is inherently safe and easy to handle, cut-to-size and install. The exterior wall activities observed during production of the test home were performed with comparable safety as the baseline process.

Quality suffered somewhat during production of the test home. Some rework was required:

- The first sheet of rigid foam installed at the end of the sidewall was removed, repositioned and reinstalled so that one vertical edge was flushed to the end of the wall and the other edge was near the center of a stud.
- The first sheet of rigid foam installed at the end of the end wall had to be recut so that one vertical edge was flushed to the outside edge of the rigid foam already installed on the sidewall and the other vertical edge was near the center of a stud.

- Several sheets of rigid foam needed to be recut for the gable. The cuts were complicated by the angles and a large ventilation louver installed in the gable wall.

In addition, a small-scale mock-up of the rigid foam building system (prior to the test) revealed that a significant number of siding nails missed a stud on two of the twenty-eight studs requiring fasteners (7 percent). The depth of the rigid foam may make it harder to hit a stud as small errors in alignment are magnified with thicker material. It was not possible to observe nail misses for the baseline process or for the test home, since the walls were closed before siding was installed.

A number of factors contributed to the rework and reduced labor efficiency observed during the test:

- The workers lacked experience with rigid foam installation. Although rigid foam was installed on the mock-up, all workers did not participate in the demonstration. The installation process was not well defined. The two teams were left to "discover" the best process and worker organization in real time. Various worker combinations were tried including: two workers up (on the rolling scaffold) and two down (on the factory floor), two up and one down, and one up and one down (similar to siding installation). Both teams eventually evolved to two workers, one up, and one down.
- The dimensions of the rigid foam sheets (48 ½" x 96"), the only product size available for the prototyping, were not ideal for the application:
    - The wall height (102") required a second 6" band of rigid foam on the side walls. This required extra cutting, handling, positioning, fastening, and taping.
    - The extra width required a stud backer or cut every two to three sheets.
- The router bit was not ideal for the application. The cutting length was too short to cut through both, the siding and foam, in a single pass, while using the framing as a guide. This resulted in two separate cut-outs for each opening, one for the foam and one for the siding. The foam cutting was easy, using a router with the framing as a guide. Cutting the siding was more difficult. It required outlining the opening (the framing could not be used as a guide) and using a hand-held circular saw. This issue can be overcome with the use of a longer router bit that would enable cutting both, the siding and the foam, in a single pass.
- Process interruptions were much more frequent as workers struggled with an undefined process, unclear roles and unfamiliar materials. This constantly disrupted the pace of the teams.

Process time estimates based on observations during production of the test home are shown in Table 7. Estimates include all work on one floor, except where otherwise noted. Where manpower varied greatly (for example, the installation of rigid foam insulation on the sidewall), average manpower was estimated. Note that estimates are based on very limited observation and, therefore, are only rough approximations.

Although longer fasteners were required to install the siding, flashing, windows, doors and trim through the siding and foam and into the frame, this change did not significantly affect the process or the times observed. In fact, the time required to install siding on one sidewall was almost identical to that of the baseline process.

Table 7: Process Time Estimates for Selected Test Activities

Activity	Clock time (mins.)	No. of workers	Labor hrs
Install 2 x 6 along eave	30	1	0.5
Cut 6 in. foam strips	5	1	0.1
Install foam on side wall	67	3	3.3
Install foam on one end wall (not including gable)	16	2	0.5
Cut siding to 102 in.	10	1	0.2
Install siding on side wall	40	2	1.3
Cut out siding from one opening	5	1	0.1

Source: The Levy Partnership, Inc.

Estimates for the marginal labor required to build the test home are shown in Table 8.

Table 8: Marginal Labor for the Test Home (Two Floors)

Activity	Labor Hrs.		
	Test home	Baseline	Margin
Install house wrap	0.0	1.0	-1.0
Install 2 in. x 6 in. lumber along eaves	1.0	0.0	1.0
Cut 6 in. rigid foam strips	0.2	0.0	0.2
Install foam on side walls	6.7	0.0	6.7
Install rigid foam on end walls (excluding gable)	1.1	0.0	1.1
Cut siding to 102 in.	0.3	0.0	0.3
Total	9.3	1.0	8.3

Source: The Levy Partnership, Inc.

The process issues discussed previously result in overstating the true marginal labor cost of installing rigid foam in the test home. Note that once the foam installation teams worked through these issues and gained some experience, they evolved to two teams of two workmen each. By the end of the test, one team demonstrated that they could install the full-size sheets of rigid foam on an end wall (excluding the gable) at a pace equal to that of siding installation in the baseline case. Assuming that this is the true pace of rigid foam installation, the true marginal labor of installing rigid foam in the test home is approximately 4.2 labor hours. Note that this estimate excludes rigid foam installation at the gables.

At a wrap-up meeting following the test, the research team reflecting on the process made the following observations and recommendations:

- A router bit with a longer cutter is needed sufficient to cut both, the rigid foam and the siding, while allowing the framing to serve as a guide.
- Getting rigid foam supplied with the proper dimensions (for example, 4' x 9') is essential.
- Foam scraps (for example, cut-outs from window/door openings) should be used as spacers on the gables. Cutting-to-size for a tight fit is not required here, since the attic is not part of the conditioned space. A more comprehensive solution would be to redesign the roof to be 2" longer to eliminate rigid foam at the gable.
- The existing door design worked for the front door of the test home with only minor changes to the trim detail. However, if there is not a perpendicular wall near the hinge side of the door (limiting the door swing beyond 90°), the deeper opening may itself limit door swing. Note that the door is located to the exterior of the opening. A door designed for a 6" wall might be a better solution.
- The rigid foam did not need to be fully fastened, since the siding nails also serve to fasten the rigid foam. Instead, just tacking each corner of the rigid foam sheets may suffice.
- With experience, the joint sealing tape can be applied efficiently and expeditiously, especially along vertical seams.
- From a housekeeping perspective, debris from cutting rigid foam with a router requires additional cleanup.

In summary, the process test demonstrated that rigid foam insulation could be successfully installed on the test home in the Karsten factory with minimal disruption. However, several design and production factors may make installation more difficult generally.

- Installation of the foam requires extra labor – approximately two additional labor hours per floor (about one additional worker for a line producing three to four floors per day). If all homes required rigid foam, foam installation could be a full time assignment for an additional worker. If rigid foam is only an option, then this labor might better be provided by a general purpose utility crew responsible for customization/optional work.
- It may require an additional workstation available for exterior wall activities. Rigid foam installation is a serial task. It must be performed after sheathing is installed (if sheathing is required) and before the installation of windows, doors and siding. Therefore, there must be sufficient workstations for an additional layer to be added to the exterior walls. This is often the case in housing factories where finished drywall is standard, since the interior requires more work than the exterior and, therefore, defines the length of the production cycle and length of the line. If there are not sufficient workstations, then it may be possible to install rigid foam at the same station (in the same production cycle) as sheathing or windows/doors. For example, the rigid foam installer might closely follow the sheathing installers or be integrated into a single rigid foam/sheathing team.

- If 2”, R-10 rigid foam is used, it will be progressively harder to hit the studs with a nail or screw gun.
- If sheathing, rigid foam and vinyl siding are all used, the design implications of installing windows and doors directly over the rigid foam need to be considered.

Full-Scale Prototyping

Full-scale prototype testing of stud walls with exterior continuous insulation (CI) was conducted on October 3, 2013 in association with partner manufacturing plant, Karsten Homes, Inc. (Sacramento, California). Karsten Homes is a subsidiary of Clayton Manufactured Homes. The exterior continuous insulation board tested was FOAMULAR® 250 XPS, an XPS product manufactured by Owens Corning.

Figure 35: Full-scale Prototyped Test Home, Karsten Homes, Sacramento California

Source: The Levy Partnership, Inc.

Test Plan

Whole-house prototyping was conducted for the selected advanced wall system. Below are the in-plant and on-site testing criteria, followed by specifications and drawings of the prototype home.

In-plant Testing Criteria

Documentation and evaluation of construction detailing and material use

An assessment was conducted of the constructed prototype with regard to developed construction details, joinery methods, material and equipment requirement and handling, skills needed and other performance and assembly attributes.

Manufacturing/production process analysis

During the prototyping and testing in plant, observation and documentation of the construction sequence including work stations involved, process teams, methods/tools/ equipment, material staging/layout, and so on. Evaluation and assessment of issues with the process and collection of data related to key metrics (cycle time, process duration, through-put, labor hours, material wastage, quality, safety and so on). Analysis of the construction process focused on impacts of incorporating CI on key performance metrics (safety, quality, timing/line flow, labor content, floor space and facility/equipment costs). The analysis will provide a measure of the impact of the anticipated changes on key production performance metrics.

On-site Testing Criteria

Transportation Test: This test is observational and performed to identify the cumulative effect of highway transportation including shock, vibration, and so on on home durability and building integrity.

Product Characteristics

This section focuses on the physical properties of the rigid insulation product used for full-scale prototyping: Owens Corning's Foamular 250 XPS.

Physical properties

Table 9: Physical Properties of XPS Insulation used for Full-Scale Prototyping

Item	Property
Insulation brand name	FOAMULAR® 250 XPS
Insulation type	Extruded polystyrene or XPS
Product thick. @R-5	1"
Perm rating @1"	1.1
Compressive strength	25 psi
Integrated water and air barrier	Yes, with JointSealR™ tape
Shear resistance	Not significant
Strengths	• Can be cut with a saw, hot wire or scored and snapped • Zero ozone depletion potential indicating negligible degradation to the ozone layer • Maintains at least 90% of its R-value over the lifetime of the product and covers all ASTM C578 properties • Contains minimum 20% recycled content • The only XPS foam to be GreenGuard Certified and with certified recycled content – certified by Scientific Certification Systems (SCS) to contain a minimum 20% recycled content
Limitations	Non-structural
Weight	Min. 1.6 pcf
Available panel sizes	• 96" x 16" or 24" or 48" • 108" x 48"
Production impact	Refer to Chapter 3, "Manufacturing Process Analysis"

Source: The Levy Partnership, Inc.

Table 10: Fastening Systems

Item	Specifications
Framing	2 x 4 @ 16" o.c.
Fasteners and tools	See Table 2
Cladding attachment	LP Smart side 7/16" – Nail (3") (http://www.lpcorp.com/smartside/panel/ , http://www.lpcorp.com/resources/literature/)
Furring or Strapping	Not required

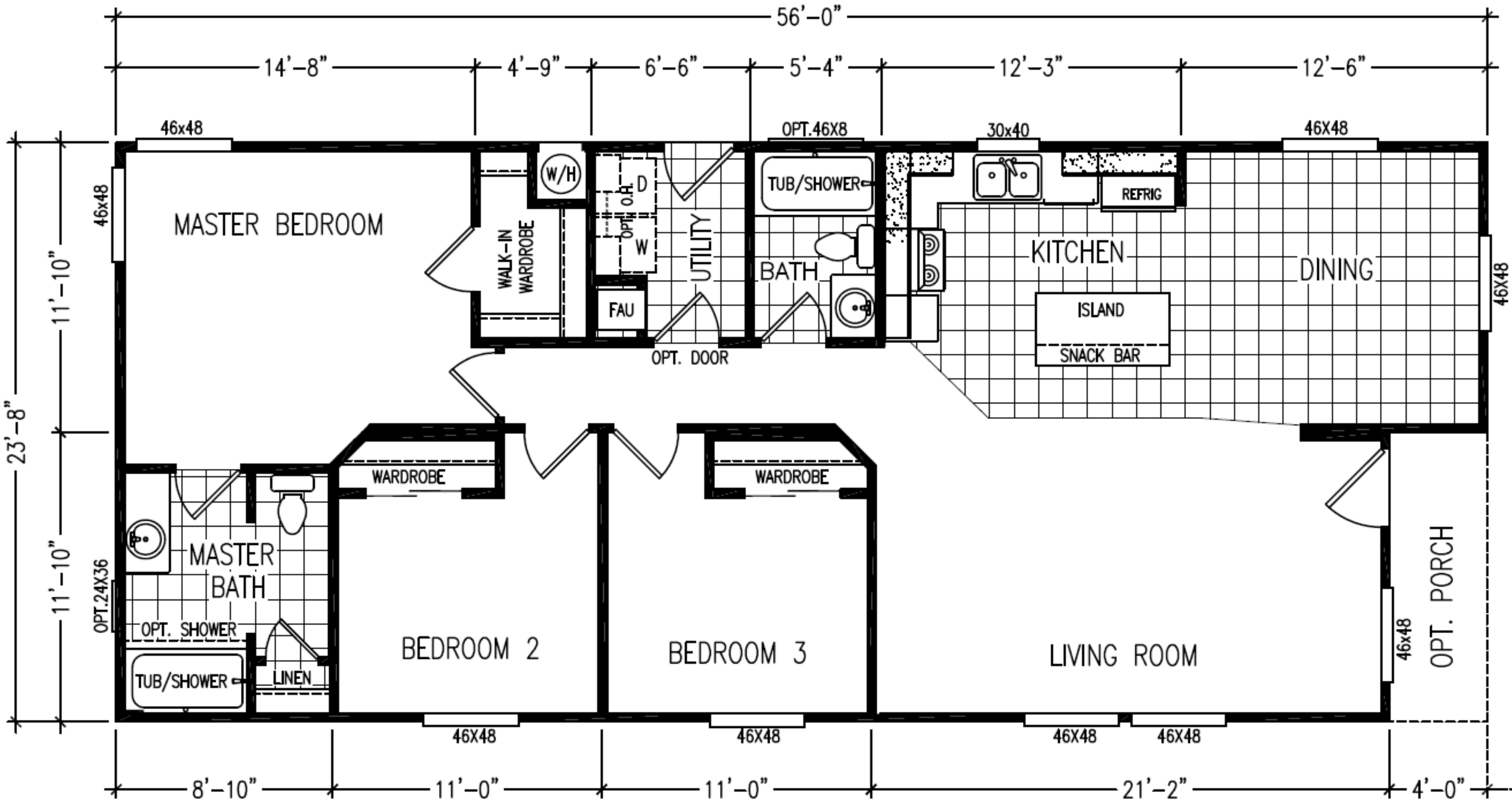
Source: The Levy Partnership, Inc.

Table 11: Product Tests and Approvals

Item	Test type
Tests completed	• Product data sheet ○ (http://www.foamular.com/assets/0/144/172/174/11b5f50a-0f80-4f08- bebe-71f4b6a9fdf7.pdf) • ICC ES Report ESR-1061 ○ (http://www.icc-es.org/reports/pdf_files/SBC/ESR-1061.pdf) • Meets ASTM C578 Type IV (Std. for rigid polystyrene insulation) ○ (http://foamular.com/assets/0/144/172/174/068b3c93-7431-43c4-8d43-53e09ea0b584.pdf) • UL Classified • ASTM E2178-03 (air permeance) • NFPA 285 (fire tested wall assemblies)
Tests required for HUD approval	Refer to Appendix A

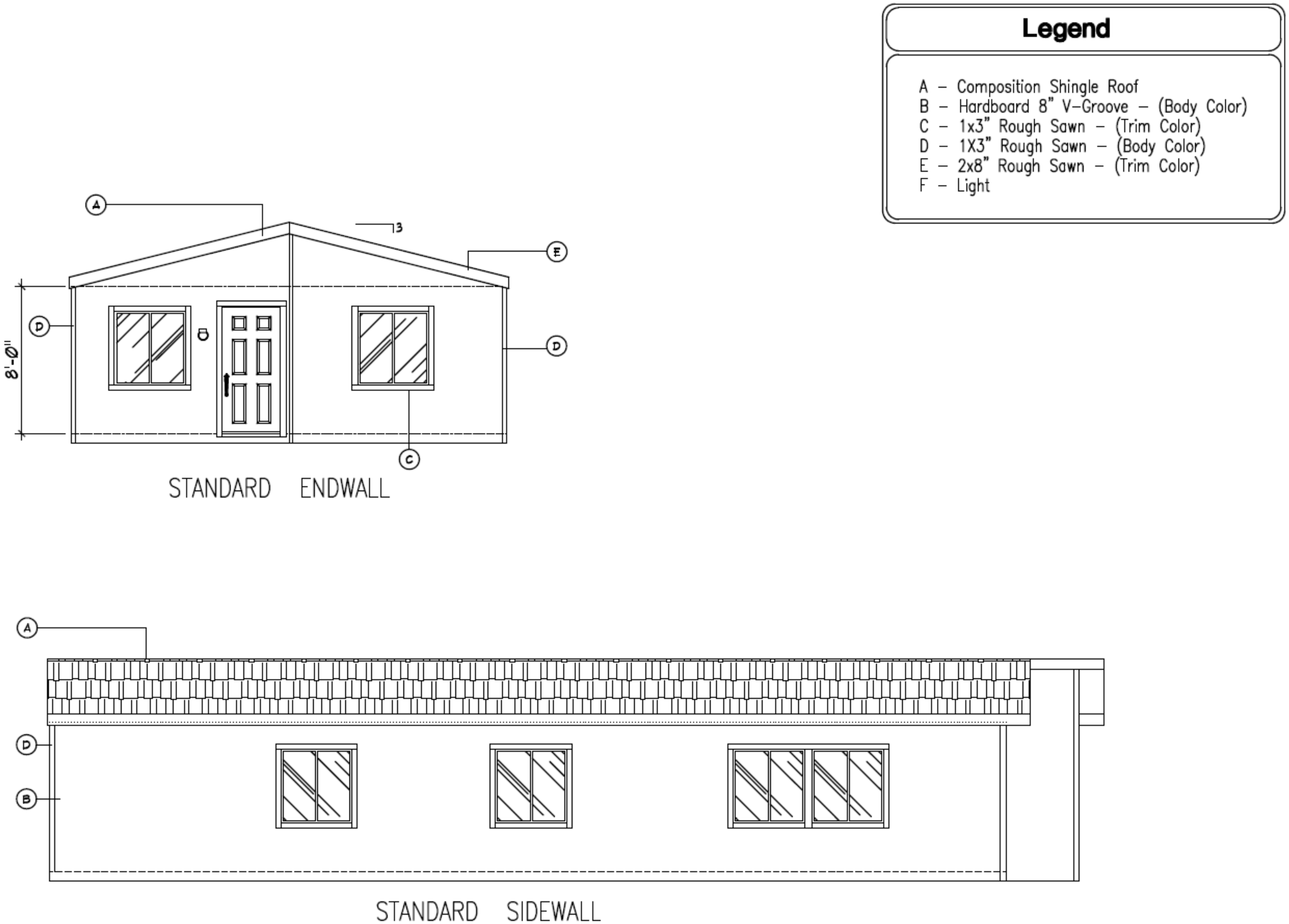
Source: The Levy Partnership, Inc.

Figure 36: Prototype Home Construction Drawings – Plan



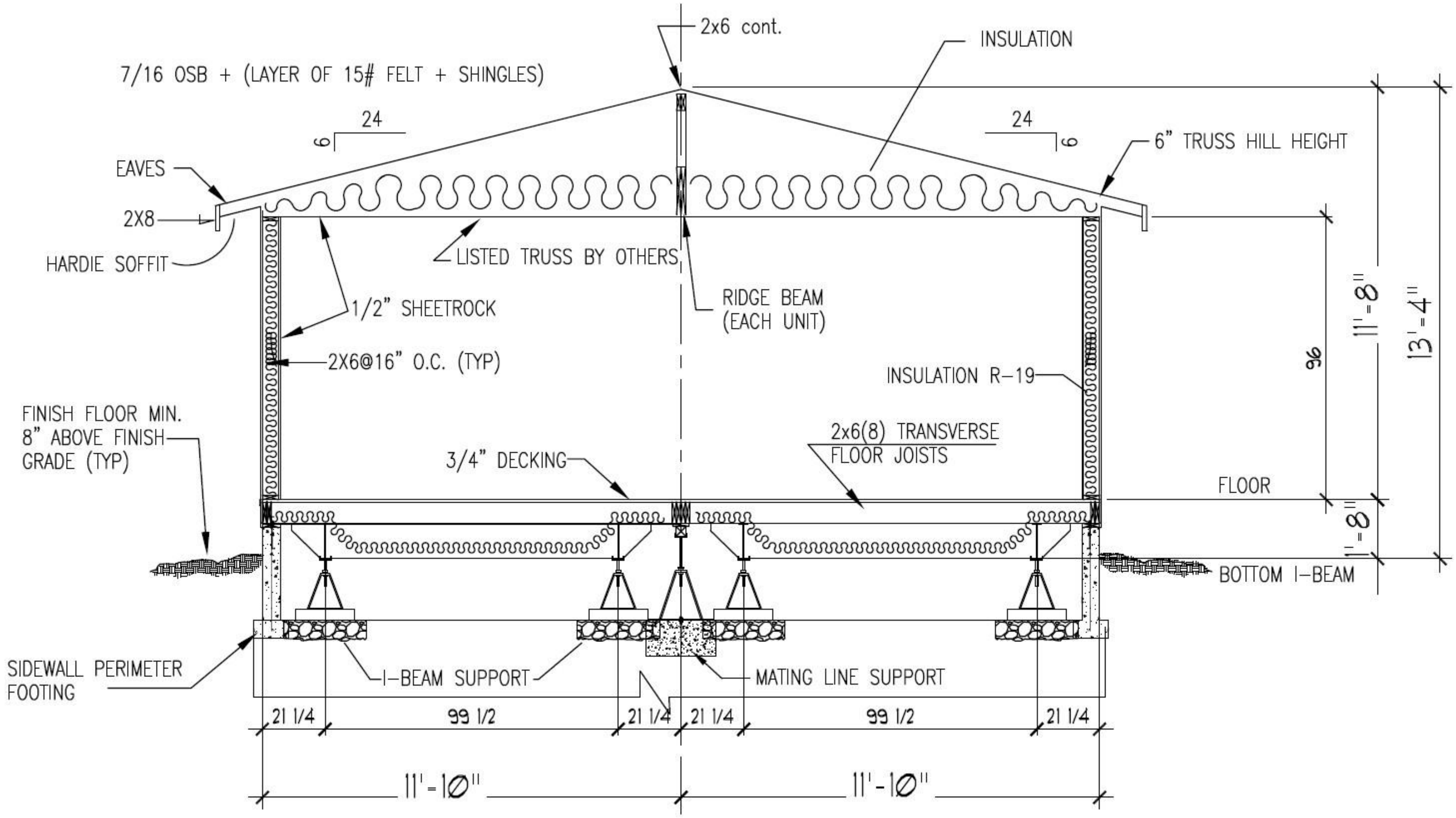
Source: The Levy Partnership, Inc.

Figure 37: Prototype Home Construction Drawings – Elevations



Source: The Levy Partnership, Inc.

Figure 38: Prototype Home Construction Drawings – Typical Cross Section



Source: The Levy Partnership, Inc.

Note: Shown figure is a typical cross-section of a manufactured home built by Karsten Homes. The prototype home has R-11 fiberglass batts in the cavity of 2x4 stud framing in the walls. There are no eaves on the prototype home.

Construction details and attachment and tools specifications are listed in Chapter 3. Table 12 lists the material and equipment needs for the full-scale prototyping effort.

Table 12: Material and Equipment Needs

Item	Description	Product code	Quantity
Materials			
FOAMULAR® 250 XPS	1” R-5 FOAMULAR® 250 XPS	--	As required
JointSealR™ foam joint tape	Water resistive and air barrier; self-adhering seam tape	--	As required
Siding			
7/16” SmartSide panel siding	4’ x 8’ @ 8”o/c	As required	
Fasteners			
Staple (Insulation fastener)	2" x 1" crown, 16 gauge Staple	P21BAB	4 ctn @ 5000 each
Nail (Siding fastener)	3" x 0.120 RS Nail	H627ASBX	6 ctn @ 2500 each
Fastening tools			
Stapling gun	WC200 XP – 16 gauge, 1” wide crown, 2” heavy wire stapler	4Y0001N	5
Nailing gun	SN951XP -4” 34 clipped head framing nailer	5B0001N	5

Source: The Levy Partnership, Inc.

Observation and Evaluation

In general, the use of CI (in this case, Owens Corning’s FOAMULAR® 250 XPS insulation board and related products) offered a solution that is fairly well-resolved with regard to construction detailing. The foam panels provide a continuous insulation layer that is durable, virtually eliminates thermal bridging, and can be installed in the plant with little training. Application of the tape to the joints enabled the material to also serve as an air and water resistive barrier, providing potential cost savings by eliminating the need for a separate material to serve this function. The relative high density and compression strength of the foam appears to be sufficient to allow the window to bear partially or entirely on the foam, enabling the use of fairly simple window and door framing details.

General observations and items that require further analysis and development are discussed below.

Construction Detailing

- Panel sizes. The exterior wall height, including the rim joist, is about 9’ but the available FOAMULAR® 250 XPS panels were 4’ x 8’ sheets. This resulted in the need to tack 6” strips along the rim joist adding a cutting and tacking operation and requiring additional taping, steps that can be eliminated by the use of 9’ boards (Figure 39).

Figure 39: Panel Sizes

Source: The Levy Partnership, Inc.

- Panel fabrication (Figure 40). The width of the foam boards supplied by the insulation manufacturer was inconsistent, ranging between 48¼” to 48½” (likely due to a fabrication error). Since the edges did not fall perfectly on each stud several workarounds were needed to secure the panel edge to framing. Initially, a backer stud was used at a few joints. Later, every second or third foam sheet was trimmed to compensate for the width variation. In both cases, there was an addition of labor and the backer board added extra lumber cost that was significant and unnecessary. This was assumed to be an isolated manufacturing error that contributed to slowing of the line flow.

Figure 40: Panel Fabrication

Source: The Levy Partnership, Inc.

- Corner framing detail was handled well without creating a thermal bridge (Figure 41). The CI was trimmed to overhang the end by 1” catching the adjacent board and providing a tight foam seal around each corner.

Figure 41: Corner Framing Detail

Source: The Levy Partnership, Inc.

Installing Windows and Doors

- Cutting openings. As noted earlier, the cutting of openings in the foam and siding requires a better resolution. For the prototype, the quality control manager took responsibility for this work by first cutting a starter hole and then using a hand-held circular saw guided by the rough framing (Figure 42). This was time consuming and occasionally imprecise. The general view was that a router with the proper bit (not available at the time of the prototyping) would resolve this problem.

Figure 42: Cutting Openings

Source: The Levy Partnership, Inc.

- Window bearing. The design of the windows results in the frame bearing entirely on the foam (Figure 43). While this detail was approved by the window manufacturer, and conforms to code, the team noted the need to assess the durability of this detail following transportation.

Figure 43: Window Bearing

Source: The Levy Partnership, Inc.

- Door jambs. Standard depth door jambs need an extra 1" blocking to the interior to provide a flush surface (Figure 44). While the door swing at the test home was not impacted, if there isn't a perpendicular wall on the hinge side of the door (limiting the door swing beyond 90°), the deeper opening may itself limit door swing. The door on the test home is located to the exterior of the opening. A door designed for a 6" wall might be a better solution.

Figure 44: Door Jambs

Source: The Levy Partnership, Inc.

Fastening and Taping

- Locating fasteners. The foam wall sheathing was tacked to the framing with 2" long, 16 gauge staples. The staples hold the insulation in place until the siding is installed with nails that secure both the siding and foam with a required framing penetration of 1½".

Because the fastening process is blind (studs are not visible from the exterior) there continues to be an issue of the staples not hitting the studs. Stud locations were approximated by measurement. However, this method is not perfect and there were a few instances where the staples did not hit the stud (Figure 45). One solution is to print stud patterns on the insulation material.

Figure 45: Locating Fasteners

Source: The Levy Partnership, Inc.

- Taping method. JointSealR™ tape was applied at all seams allowing the CI to perform serves as the weather- and air barrier (Figure 46). Taping is a two-person job and was considered fairly easy despite early concerns that tape application would significantly impact quality and production speed. Still, the hand application added labor and is among the potential areas for improvement. One suggestion was to try various taping tools that could be used on the main production line.

Figure 46: Taping Method

Source: The Levy Partnership, Inc.

Assembly/Production

- Line stoppage. The Karsten team made the decision to complete all of the sheathing and finishing operations in a single station rather than spread tasks out over several stations. Additional staff was assigned to the prototype effort unbalancing the line and slowing work on other homes. This was an expedient solution for the prototype but is clearly not a model for routine production. Concentrating work at a single station distorted flow and made it difficult to quantify the impact of adding foam to overall plant cycle time. However, as a general observation, the staff did an excellent job of adapting to a new material, problems were resolved quickly, and the operations on the prototype did not appear to add significantly to production time. This bodes well for future production using foam sheathing.

Figure 47: Line Stoppage

Source: The Levy Partnership, Inc.

On-site Testing Results

The test home was subject to a transportation test, a visual inspection and observational evaluation performed to identify the cumulative effect of highway transportation including shock, vibration and so on, on wall durability and performance.

The home was inspected twice; first upon arrival at the destination site and subsequently after the installation process was completed. Initial inspection of the unit, conducted on November 4, 2013, reported no indications of separation of panels and no visual signs of nail pops or loosened connections; the obvious potential modes of failure. There were a few interior wall cracks, not uncommon to factory built homes transported over the road. Following setting of the home on site, the second inspection was conducted on November 21, 2013. No other visually-evident defects or degradation were noted as a result of the installation and setting process. Overall, no damage to the home was observed that could be attributed to the additional layer of exterior CI on the walls.

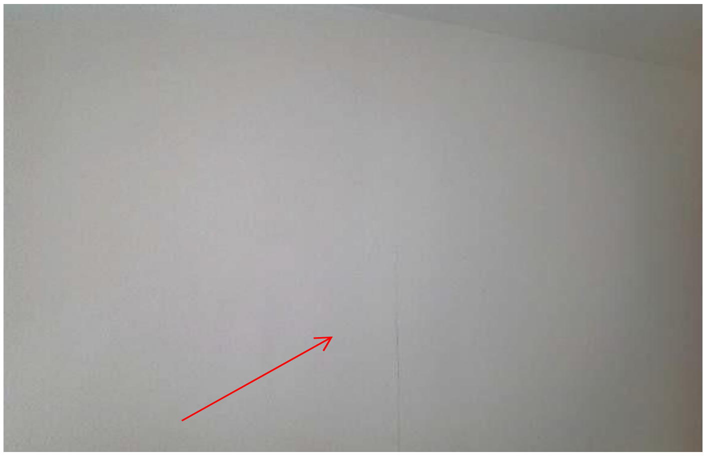
Figure 48: No Damage to Exterior Walls of Test Home: End Wall

Source: The Levy Partnership, Inc.

Figure 49: No Damage to Exterior Walls of Test Home: Side Wall

Source: The Levy Partnership, Inc.

Figure 50: Interior Wall Crack on Test Home



Source: The Levy Partnership, Inc.

CHAPTER 4: Roofs

Similar to the advanced wall designs described in Chapter 3, advanced roof designs were developed with the goal of developing cost effective roof solutions that would meet the prescriptive requirements of the IECC 2012 standards. The technical team followed an iterative process of selecting and eliminating advanced roof systems in collaboration with the Technical Steering Committee (TSC). Following a preliminary design development of eight identified options, a qualitative assessment was conducted for the selected technologies. The advisory committee and industry experts rated the options and selected four options for subsequent research. Table 13 compares the specifics of the four roof assemblies with the base case.

The four roof concepts were further developed and refined. The technical team and the industry advisory committee discussed the findings and identified those that were most cost-effective and had potential wide market appeal and application (potentially attractive to most manufacturers). Subsequently, one technology – based on the use of compressed or dense-packed insulation at eaves – was deemed by the committee as having the greatest commercial potential.

The following section discusses the specifications and design of the four advanced roof solutions and analyses their performance in the manufactured housing industry.

Roof Performance Specifications

Initially, the TSC and the technical team analyzed and assessed eight roof design options based on their energy performance, cost, manufacturability and other criteria. The review focused on evaluating the prospective benefits and drawbacks of each of the technologies when used in the factory built setting. The evaluation culminated in the selection of four roof options to move forward to the next phase – advanced design development. Following are the four selected roof options that were chosen for further development:

- Design 1: Vented attic roof with dense-packed insulation at eaves
- Design 2: Vented attic roof with compressed batts at eaves
- Design 3: Vented, sealed attic roof with dense-packed blown insulation at the eaves
- Design 4: Unvented, sealed attic roof with dense-packed blown insulation at the eaves

The selected designs were developed into detailed design solutions, including specifics such as dimensions, insulation materials, component assemblies, and so on. The following section compares the four roof options against a base case, which is conventional roof construction, and provides a brief description of each of the selected design solutions. Construction details were developed for incorporation in both; single-section and double-section manufactured homes.

Table 13: Advanced Roof Design Options: Specifications and Assembly

Specs	Base Design	Design 1	Design 2	Design 3	Design 4
Roof design	Conventional roof	Vented attic roof with dense-packed insulation at eaves.	Vented attic roof with compressed batts at eaves.	Vented, sealed attic roof with dense-packed blown insulation at the eaves.	Unvented, sealed attic roof with dense-packed blown insulation at the eaves
Description	Conventional roof construction with standard density blown insulation.	Dense-packed blown insulation to increase the thermal performance at the eaves. Standard density loose fill insulation at the center of the attic.	Combines two types of insulation to achieve a more uniform U-value across the attic; blown/loose-fill insulation at the center with compressed, unfaced batt insulation at the eaves.	Sealed attic roof with dense-packed insulation at the eaves and standard density blown insulation in the field. An air barrier with a high perm rating is used to seal the attic.	Sealed attic with dense-packed blown insulation at the eaves and standard density blown insulation in the field. Diffusion vent (a vapor permeable air barrier vent) used at the ridge to allow accumulated moisture to dry out via vapor diffusion while still acting as an
Roof frame	Truss w 2x2 chords @ 16" / 24" o.c.				
Roof Insulation (Type, R-value)	Standard density blown insulation in the field and at eaves.	Standard density blown insulation in the field, dense-packed at eaves.	Standard density blown insulation in the field, unfaced compressed FG batts at eaves.	Standard density blown insulation in the field, dense-packed at eaves.	Standard density blown insulation in the field, dense-packed at eaves.
Ventilation	Vented	Vented	Vented	Vented	Unvented
Ventilation type	Cardboard baffle with ridge vents.	Cardboard baffle with ridge vents.	Cardboard baffle with ridge vents.	1.5" x 1" spacers on truss, with ridge	n/a
Air barrier	n/a	n/a	n/a	Vapor permeable air membrane around the roof truss cavity.	Diffusion vent with a vapor permeable air barrier at the ridge.
Roof finish	Asphalt shingles with underlayment				

Source: The Levy Partnership, Inc.

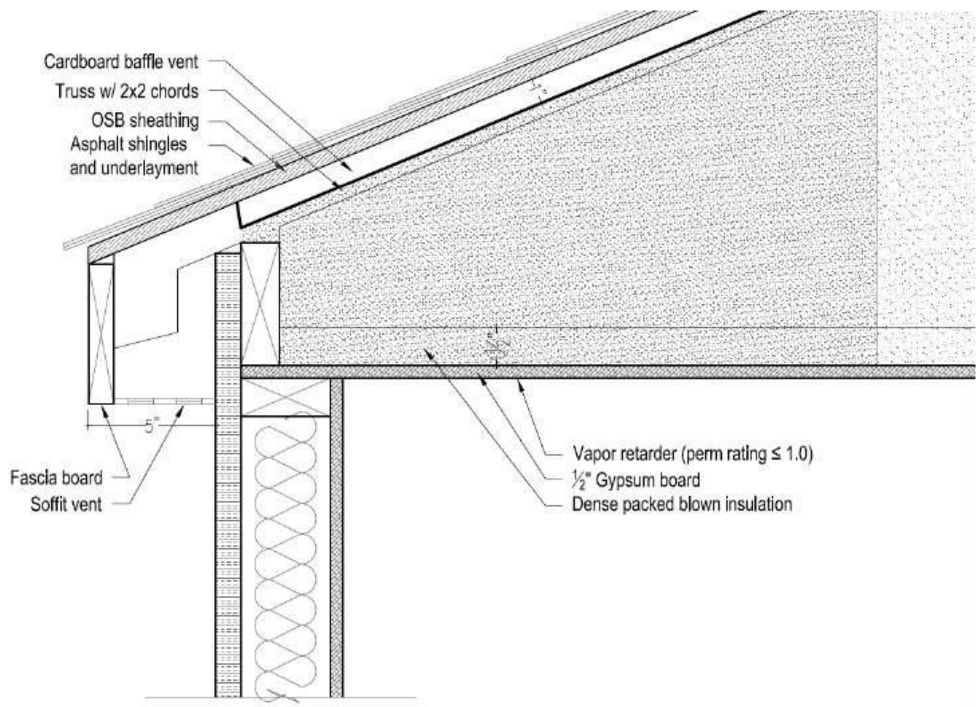
Advanced Roof Design Development

This section provides a detailed description of the design and construction of the four advanced roof design assemblies.

Design 1: Vented Attic Roof with Dense-packed Insulation at Eaves Concept

This roof design uses dense-packed/compressed blown insulation to increase the thermal performance at the eaves. The field of the attic is covered with standard density loose fill insulation. Vent path is provided by a cardboard baffle or by comparable means.

Figure 51: Design 1 - Eave Detail (Single-Section/Double-Section Construction)



Source: The Levy Partnership, Inc.

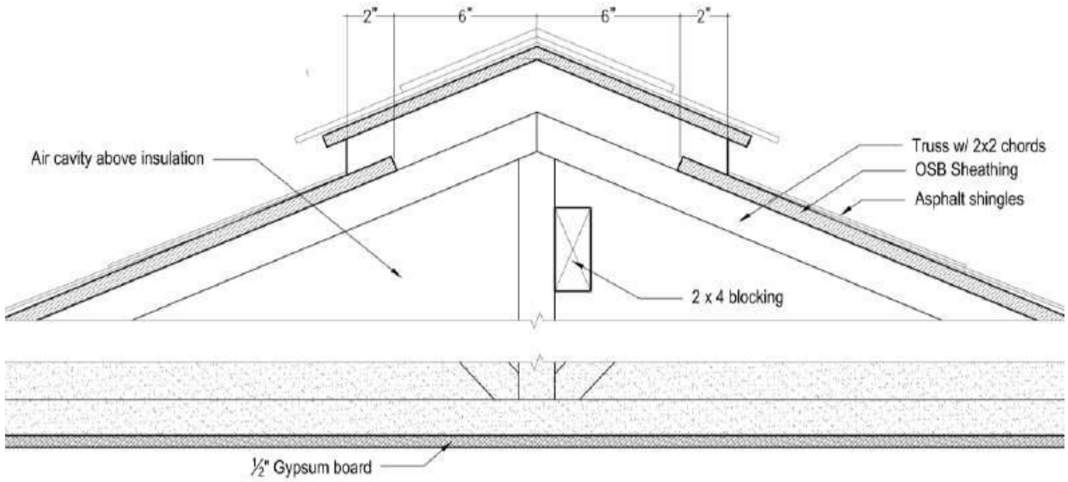
Advantages

- Improves thermal performance in an area that, typically, is a thermal weak spot.
- Small change from current practice with modest impact on the production process.
- No new materials, although a baffle is recommended to provide vent path.
- Blown insulation insulates between the truss chords.

Limitations

- Some extra labor and care associated with creating the baffle and packing in the insulation using a special mold.
- May need different baffle geometries to match various roof/ceiling slope combinations.

Figure 52: Design 1/ Design 2 - Ridge Detail (Single-Section Construction)

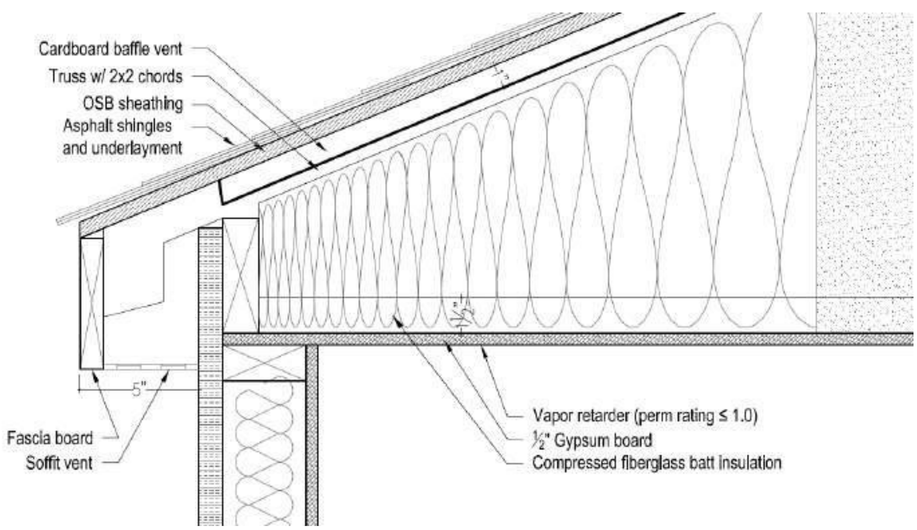


Source: The Levy Partnership, Inc.

Design 2: Vented Attic Roof with Compressed Batts at Eaves Concept

This roof design is a variation on Design 1 and combines two types of insulation to achieve a more uniform U-value across the attic; blown/loose-fill insulation at the center with compressed, unfaced batt insulation at the eaves.

Figure 53: Design 2 - Eave Detail (Single-Section/Double-Section Construction)



Source: The Levy Partnership, Inc.

Advantages

- Like the previous design it improves thermal performance in an area that typically is a thermal weak spot.

- Assured consistency of the density and R-value in the compressed batts area.
- Small change from current practice with modest impact on the production process.
- Compared with Design 1, requires less labor to install.

Limitations

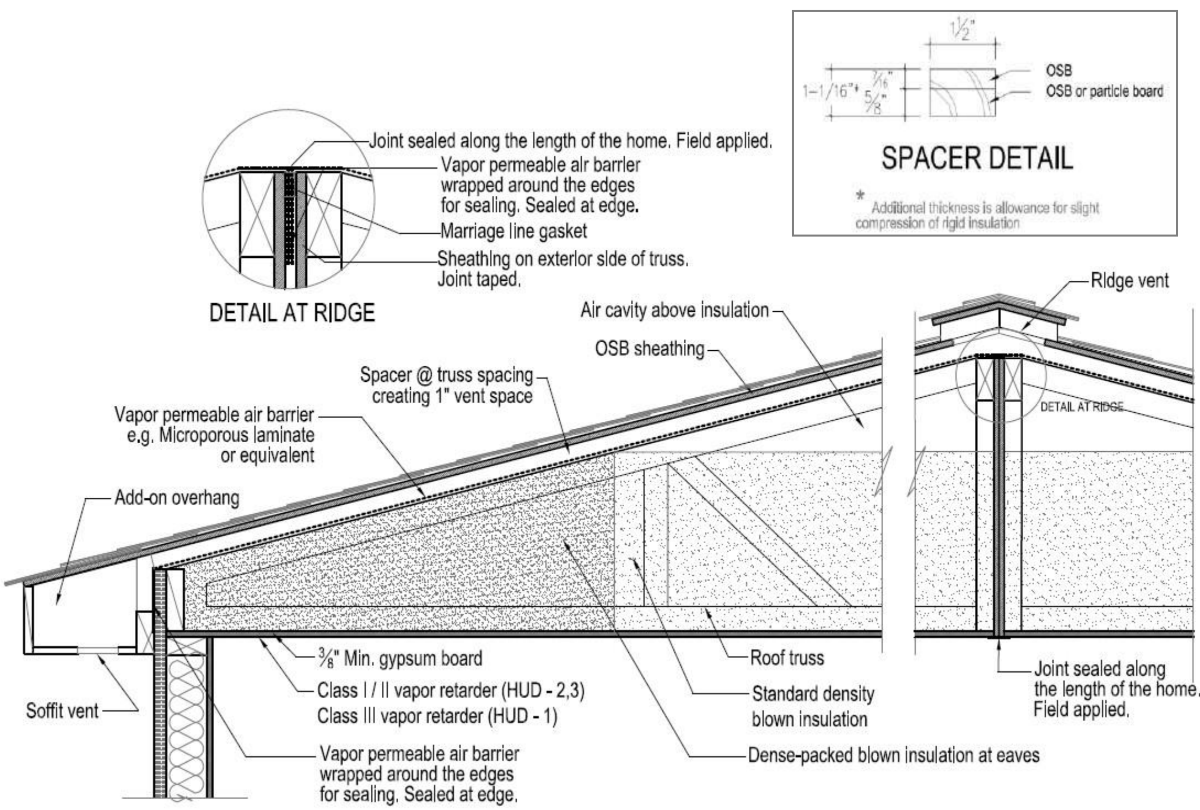
- Extra prep work associated with trimming unfaced batts to fit within the truss bays.
- Batts don't insulate well between the truss chords losing some U-value benefit.

Design 3: Vented, sealed attic roof with dense-packed blown insulation at the eaves

Concept

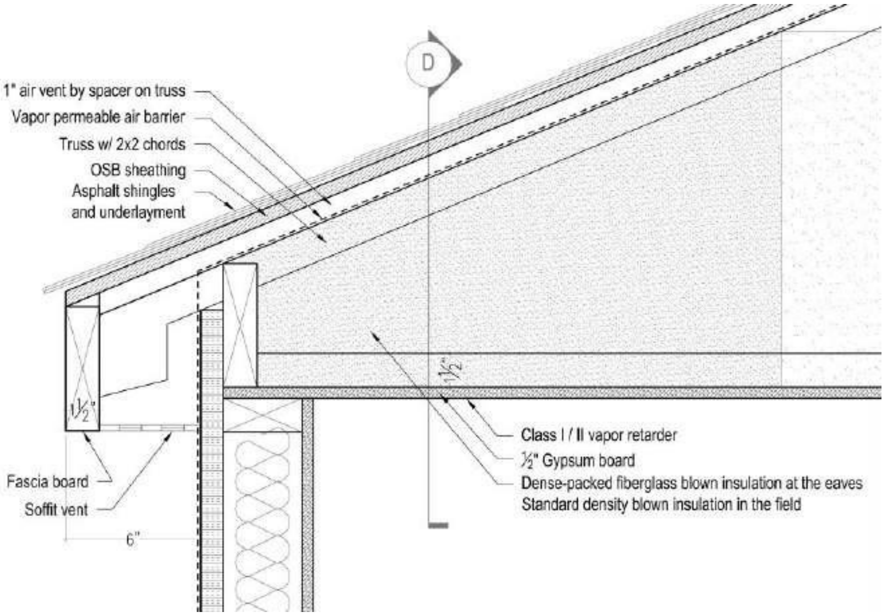
This roof design is a vented, sealed attic roof with dense-packed insulation at the eaves and standard density blown insulation in the field. An air barrier with a high perm rating is used to seal the attic.

Figure 54: Design 3 - Eave and Ridge Detail (Double-Section Construction)



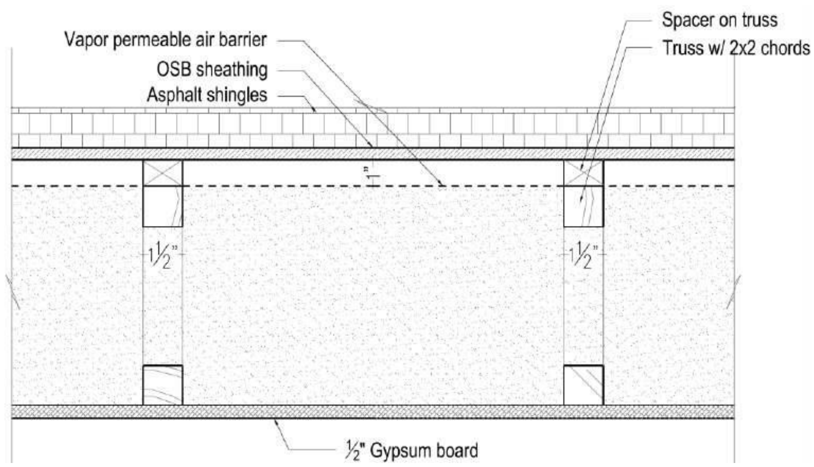
Source: The Levy Partnership, Inc.

Figure 55: Design 3 - Eave Detail (Single-Section Construction)



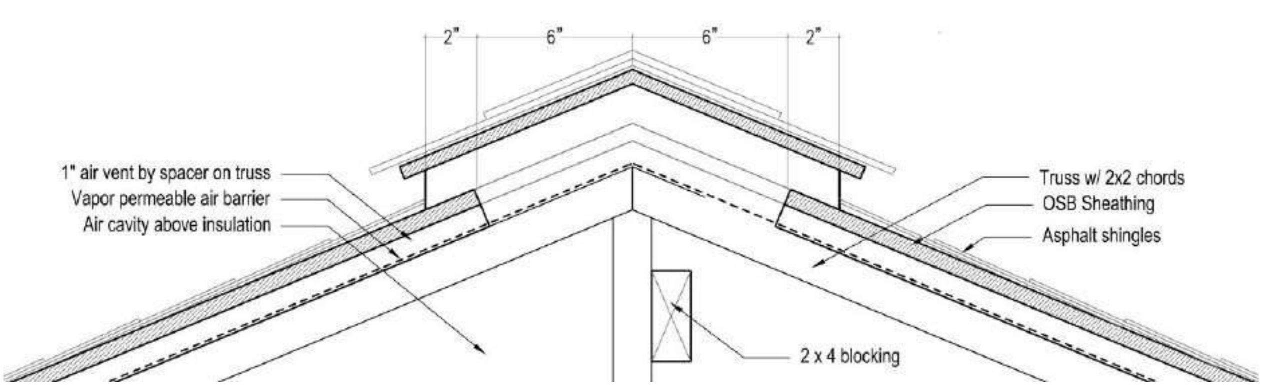
Source: The Levy Partnership, Inc.

Figure 56: Detail at D



Source: The Levy Partnership, Inc.

Figure 57: Design 3 - Ridge Detail (Single-Section Construction)



Source: The Levy Partnership, Inc.

Advantages

- Continuous air barrier around the attic eliminates air flow and helps reduce the heating and cooling load on the mechanical system.

Limitations

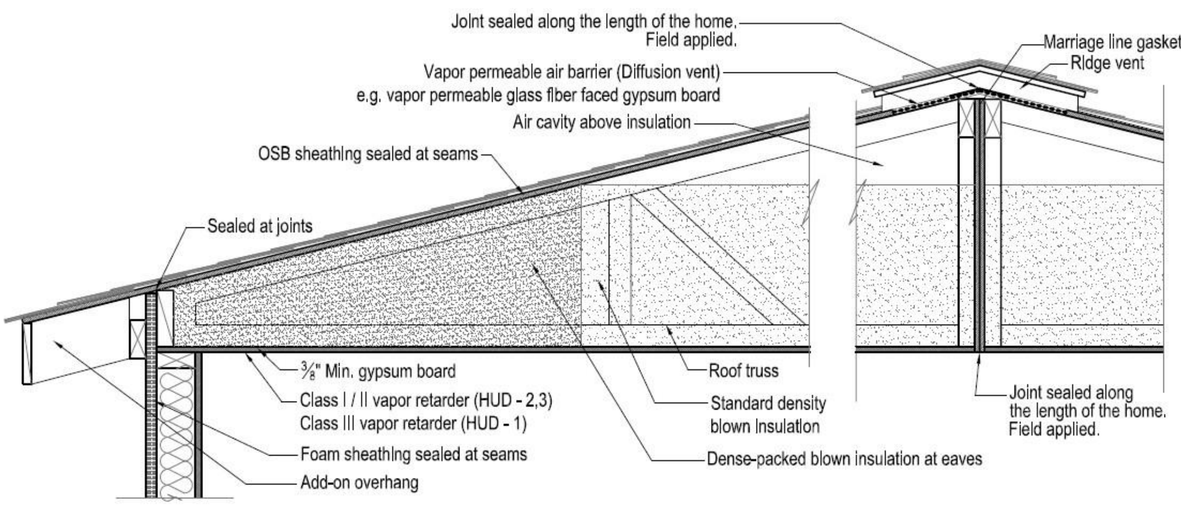
- Would require installation of roof spacers to provide ventilation space, adding lumber and labor.
- Difficulty in incorporating a hinge would limit construction to moderate slope roofs and single section units.

Design 4: Unvented, Sealed Attic Roof with Dense-packed Blown Insulation at Eaves

Concept

This roof option incorporates an unvented, sealed attic with dense-packed blown insulation at the eaves and standard density blown insulation in the field area.

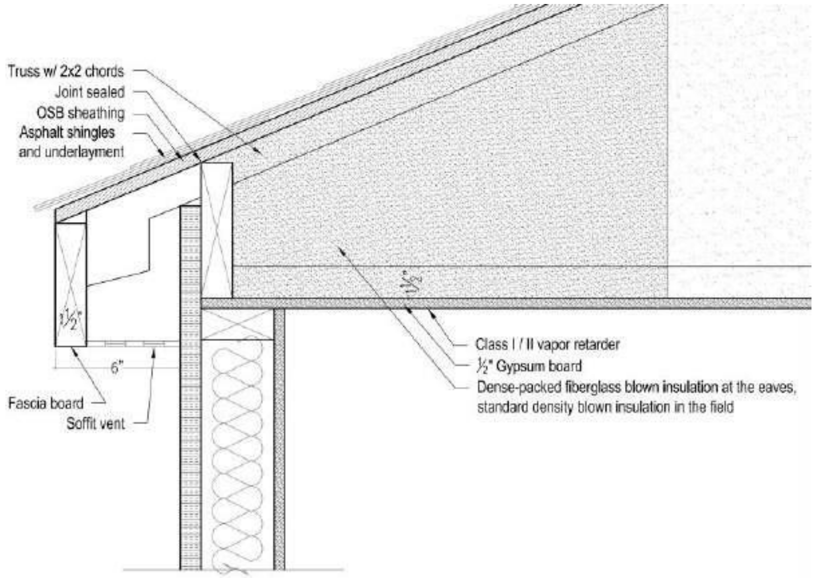
Figure 58: Design 4 - Eave and Ridge Detail (Double-Section Construction)



Source: The Levy Partnership, Inc.

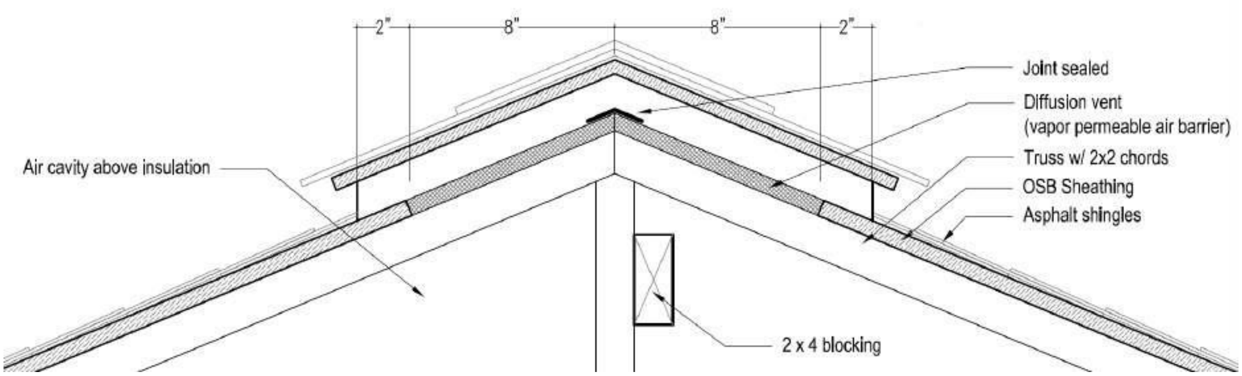
A diffusion vent (a vapor permeable air barrier vent) is used at the ridge that would allow the accumulated moisture to dry out via vapor diffusion while still acting as an effective air barrier.

Figure 59: Design 4 - Eave Detail (Single-Section Construction)



Source: The Levy Partnership, Inc.

Figure 60: Design 4 - Ridge Detail (Single-Section Construction)



Source: The Levy Partnership, Inc.

Advantages

- Continuous air barrier around the attic eliminates air flow and helps reduce the heating and cooling load on the mechanical system.

Limitations

- Sealing all around the attic roof might prove to be a challenge.
- Difficulty in incorporating a hinge would limit construction to moderate slope roofs and single section units.

Thermal and Cost Benefit Analysis

To compare and evaluate the four selected roof design options, the team conducted a preliminary cost and thermal performance assessment, contrasted with a standard base case. Table 14 shows an analysis of the thermal performance and material costs of all the roof options under consideration, including various possible combinations for the selected roof options that meet the U- value of the base case (0.024). The costs are color coded to identify the more economical solutions. The base range in green was specified as the cost of the base case + $100. Costs in blue are solutions that cost less than this range. Costs in orange are base range +$500 or less, while figures in red are significantly more.

The Technical Steering Committee conducted a qualitative assessment of the commercial potential of the concepts based on the information provided above. The evaluation culminated in the selection of Designs 1 and 2 to move forward in the research. Designs 4A and 4B were eliminated due to high costs and significant hurdles in code compliance.

Two new roof options were developed by the technical team, that were embraced by the Committee. Both options were based on the concept of using an air barrier to restrict the air flow from the roof cavity thus eliminating heat loss. The idea also stressed on adequate vapor transmission through the barrier to avoid potential moisture issues.

This task ended in the selection of the following roof designs to move further in the research effort:

- Design 1: Vented attic roof with dense-packed insulation at eaves
- Design 2: Vented attic roof with compressed batts at eaves
- Design 3: Vented, sealed attic roof with dense-packed blown insulation at the eaves
- Design 4: Unvented, sealed attic roof with dense-packed blown insulation at the eaves

Moisture Analysis

The team conducted moisture analysis of the selected roof designs in conjunction with the laboratory testing and evaluation effort, discussed in more detail in Chapter 6.

Code Compliance

Following the preliminary development of the eight advanced roof solutions, based on the specifications developed, they were analyzed for code compliance. Summaries on all the ten developed designs (in addition to the initial eight concepts two more were added with minor variations) were submitted to two leading third party agencies for review and approval under the codes and standards that regulate the construction of factory built homes. The summaries included a discussion of the advantages and challenges posed by each and construction details of connections to attached building components

Table 14: Cost and Thermal Performance Assessment of Roof Options

16" o.c.

	Lumber size	Insulation specs: Cavity	Insulation specs: Exterior/ Compressed	Total	Thermal performance: U-value	Thermal performance: Avg. R-value
Base	Truss w/2 x 2 chords	FG blown (R-52)	None	$1,053	0.024	40.92
Design 1	Truss w/2 x 2 chords	FG blown (R-49)	Dense packed at eaves	$ 1,076	0.022	44.80
		CE blown (R-49)	Dense packed at eaves	$ 1,200	0.023	43.88
Design 2	Truss w/2 x 2 chords	FG blown (R-49)	R-38 FG batts compressed to R-28	$ 1,058	0.023	44.01
		CE blown (R-49)	R-38 FG batts compressed to R-28	$ 1,144	0.023	44.13
Design 4A (Vented)	Truss w/2 x 2 chords	FG batts - 5.5"	5" EPS (R-20)	$ 2,640	0.024	42.04
		FG batts HD - 5.5"	4.5" EPS (R-18)	$ 2,528	0.024	41.99
		FG batts - 7.5"	4.5" EPS (R-18)	$ 2,529	0.023	42.74
		FG batts - 8.5"	3.5" EPS (R-14)	$ 2,262	0.024	41.33
		FG batts - 10.25"	2.5" EPS (R-10)	$ 1,886	0.024	41.14
		FG batts HD - 8.25"	2.5" EPS (R-10)	$ 1,933	0.024	42.17
		FG batts - 12"	1.5" EPS (R-6)	$ 1,623	0.023	42.82
		FGbatts HD-10.25"	1" EPS (R-4)	$ 1,575	0.024	42.36
		Blown FG - R-38	1" EPS (R-4)	$ 1,291	0.024	41.20
		Blown FG - R-40	1" EPS (R-4)	$ 1,306	0.024	42.33
		Blown FG - R-42	0.5" EPS (R-2)	$ 1,136	0.024	41.26
		Blown CE - R-38	1" EPS (R-4)	$ 1,337	0.024	42.31
		Blown CE - R-40	0.5" EPS (R-2)	$ 1,183	0.024	41.62
		Blown CE - R-42	0.5" EPS (R-2)	$ 1,207	0.023	42.79
Design 4B (Unvented)	Truss w/2 x 2 chords	FG batts - 5.5""	5" EPS (R-20)	$ 2,676	0.024	41.04
		FG batts HD - 5.5"	4.5" EPS (R-18)	$ 2,564	0.024	40.99
		FG batts - 7.5"	4.5" EPS (R-18)	$ 2,565	0.024	41.74
		FG batts - 8.5"	4" EPS (R-16)	$ 2,475	0.024	42.33
		FG batts - 10.25"	3" EPS (R-12)	$ 2,100	0.024	42.15
		FG batts HD - 8.25"	2.5" EPS (R-10)	$ 1,969	0.024	41.17
		FG batts - 12"	1.5" EPS (R-6)	$ 1,659	0.024	41.78
		FGbatts HD-10.25"	1" EPS (R-4)	$ 1,611	0.024	41.33
		Blown FG - R-38	1.5" EPS (R-6)	$ 1,505	0.024	42.23
		Blown FG - R-40	1" EPS (R-4)	$ 1,342	0.024	41.29
		Blown FG - R-42	1" EPS (R-4)	$ 1,349	0.024	42.31
		Blown CE - R-38	1" EPS (R-4)	$ 1,373	0.024	41.29
		Blown CE - R-40	1" EPS (R-4)	$ 1,397	0.023	42.65
		Blown CE - R-42	0.5" EPS (R-2)	$ 1,243	0.024	41.74

24" o.c.

	Lumber size	Insulation specs: Cavity	Insulation specs: Exterior/ Compressed	Total	Thermal performance: U-value	Thermal performance: Avg. R-value
Base						
Design 1	Truss w/2 x 2 chords	FG blown (R-49)	Dense packed at eaves	$ 920	0.023	43.90
		CE blown (R-49)	Dense packed at eaves	$ 1,044	0.023	43.96
Design 2	Truss w/2 x 2 chords	FG blown (R-49)	R-38 FG batts compressed to R-28	$ 902	0.023	44.07
		CE blown (R-49)	R-38 FG batts compressed to R-28	$ 988	0.023	44.20
Design 4A (Vented)	Truss w/2 x 2 chords	FG batts - 5.5"	5" EPS (R-20)	$ 2,495	0.024	42.08
		FG batts HD - 5.5"	4.5" EPS (R-18)	$ 2,387	0.024	42.04
		FG batts - 7.5"	4.5" EPS (R-18)	$ 2,387	0.023	42.76
		FG batts - 8.5"	3.5" EPS (R-14)	$ 2,124	0.024	41.35
		FG batts - 10.25"	2.5" EPS (R-10)	$ 1,748	0.024	41.16
		FG batts HD - 8.25"	2.5" EPS (R-10)	$ 1,797	0.024	42.22
		FG batts - 12"	1.5" EPS (R-6)	$ 1,489	0.023	42.86
		FGbatts HD-10.25"	1" EPS (R-4)	$ 1,447	0.024	42.41
		Blown FG - R-38	1" EPS (R-4)	$ 1,135	0.024	41.25
		Blown FG - R-40	1" EPS (R-4)	$ 1,150	0.024	42.38
		Blown FG - R-42	0.5" EPS (R-2)	$ 980	0.024	41.32
		Blown CE - R-38	1" EPS (R-4)	$ 1,181	0.024	42.37
		Blown CE - R-40	0.5" EPS (R-2)	$ 1,027	0.024	41.67
		Blown CE - R-42	0.5" EPS (R-2)	$ 1,051	0.023	42.84
Design 4B (Unvented)	Truss w/2 x 2 chords	FG batts - 5.5""	5" EPS (R-20)	$ 2,531	0.024	41.08
		FG batts HD - 5.5"	4.5" EPS (R-18)	$ 2,423	0.024	41.04
		FG batts - 7.5"	4.5" EPS (R-18)	$ 2,423	0.024	41.76
		FG batts - 8.5"	4" EPS (R-16)	$ 2,338	0.024	42.35
		FG batts - 10.25"	3" EPS (R-12)	$ 1,961	0.024	42.17
		FG batts HD - 8.25"	2.5" EPS (R-10)	$ 1,833	0.024	41.21
		FG batts - 12"	1.5" EPS (R-6)	$ 1,525	0.024	41.82
		FGbatts HD-10.25"	1" EPS (R-4)	$ 1,483	0.024	41.39
		Blown FG - R-38	1.5" EPS (R-6)	$ 1,349	0.024	42.28
		Blown FG - R-40	1" EPS (R-4)	$ 1,186	0.024	41.34
		Blown FG - R-42	1" EPS (R-4)	$ 1,193	0.024	42.37
		Blown CE - R-38	1" EPS (R-4)	$ 1,217	0.024	41.34
		Blown CE - R-40	1" EPS (R-4)	$ 1,241	0.023	42.71
		Blown CE - R-42	0.5" EPS (R-2)	$ 1,087	0.024	41.80

Modified 24" o.c.

	Lumber size	Insulation specs: Cavity	Insulation specs: Exterior/ Compressed	Total	Thermal performance: U-value	Thermal performance: Avg. R-value
Base						
Design 1						
Design 2						
Design 4A (Vented)	Truss w/2 x 2 chords	FG batts - 5.5"	5" EPS (R-20)	$ 2,489	0.024	42.11
		FG batts HD - 5.5"	4.5" EPS (R-18)	$ 2,383	0.024	42.08
		FG batts - 7.5"	4.5" EPS (R-18)	$ 2,383	0.023	42.85
		FG batts - 8.5"	3.5" EPS (R-14)	$ 2,125	0.024	41.52
		FG batts - 10.25"	2.5" EPS (R-10)	$ 1,748	0.024	41.78
		FG batts HD - 8.25"	2.5" EPS (R-10)	$ 1,799	0.024	42.43
		FG batts - 12"	1" EPS (R-4)	$ 1,315	0.024	42.47
		FG batts HD - 10.25"	1" EPS (R-4)	$ 1,457	0.024	42.46
		Blown FG - R-38	1" EPS (R-4)	$ 1,117	0.024	41.30
		Blown FG - R-40	1" EPS (R-4)	$ 1,132	0.024	42.43
		Blown FG - R-42	0.5" EPS (R-2)	$ 962	0.024	41.37
		Blown CE - R-38	1" EPS (R-4)	$ 1,163	0.024	42.42
		Blown CE - R-40	0.5" EPS (R-2)	$ 1,009	0.024	41.73
		Blown CE - R-42	0.5" EPS (R-2)	$ 1,033	0.023	42.90
Design 4B (Unvented)	Truss w/2 x 2 chords	FG batts - 5.5"	5" EPS (R-20)	$ 2,525	0.024	41.11
		FG batts HD - 5.5"	4.5" EPS (R-18)	$ 2,419	0.024	41.08
		FG batts - 7.5"	4.5" EPS (R-18)	$ 2,420	0.024	41.85
		FG batts - 8.5"	4" EPS (R-16)	$ 2,339	0.024	42.56
		FG batts - 10.25"	3" EPS (R-12)	$ 1,961	0.023	42.82
		FG batts HD - 8.25"	2.5" EPS (R-10)	$ 1,835	0.024	41.46
		FG batts - 12"	1" EPS (R-4)	$ 1,351	0.024	41.45
		FG batts HD - 10.25"	1" EPS (R-4)	$ 1,493	0.024	42.46
		Blown FG - R-38	1.5" EPS (R-6)	$ 1,331	0.024	42.33
		Blown FG - R-40	1" EPS (R-4)	$ 1,168	0.024	41.39
		Blown FG - R-42	1" EPS (R-4)	$ 1,175	0.024	42.42
		Blown CE - R-38	1" EPS (R-4)	$ 1,200	0.024	41.40
		Blown CE - R-40	1" EPS (R-4)	$ 1,223	0.023	42.76
		Blown CE - R-42	0.5" EPS (R-2)	$ 1,069	0.024	41.86

LEGEND

Color code	Cost (per home)
Cyan	Base range minus $100 or more
Green	Base range (± $100 from Base cost)
Yellow	Base range + $100 to $500
Red	Base range + $500 or greater

Source: The Levy Partnership, Inc.

Both RADCO and NTA performed research to ensure that the proposed roof designs are able to meet the requirements within the Manufactured Home Construction and Safety Standards. The selected roof design was reviewed for code compliance and passed according to both third parties. A brief summary of the research from RADCO and NTA is available in Appendix A.

Component Prototyping

Component prototyping of advanced roof designs was conducted in November 2014 in association with partner manufacturing plant – Golden West Homes, Perris, California. Golden West Homes is a subsidiary of Clayton Manufactured Homes.

Figure 61: Component Prototype Roof and Wall Build, Golden West Homes, Perris, California

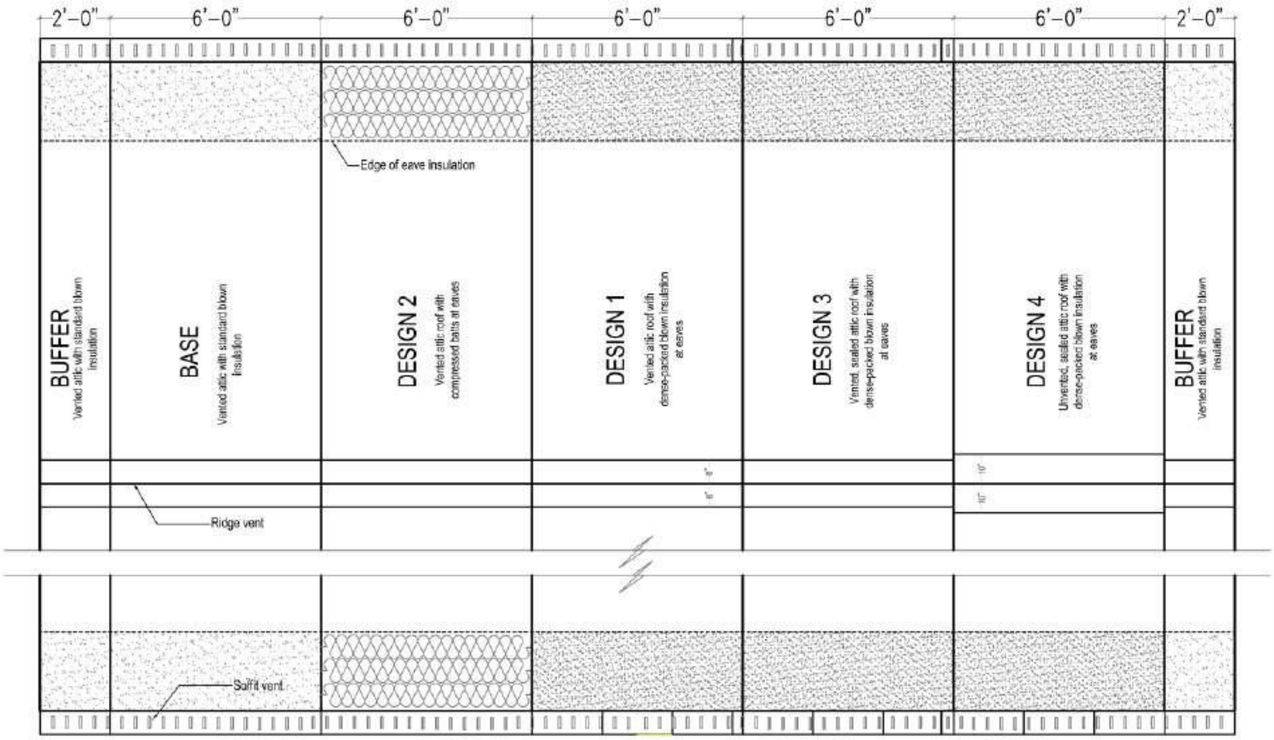
Source: The Levy Partnership, Inc.

Test Plan

The purpose of this task was to prototype build four advanced designs developed in the previous tasks. These prototype samples were evaluated for issues associated with system assembly and tested for improved thermal performance, propensity to moisture issues and structural stability.

The four advanced designs used as part of this component prototyping task are shown in Figure 62.

Figure 62: Prototyping and Testing Unit – Roof Layout

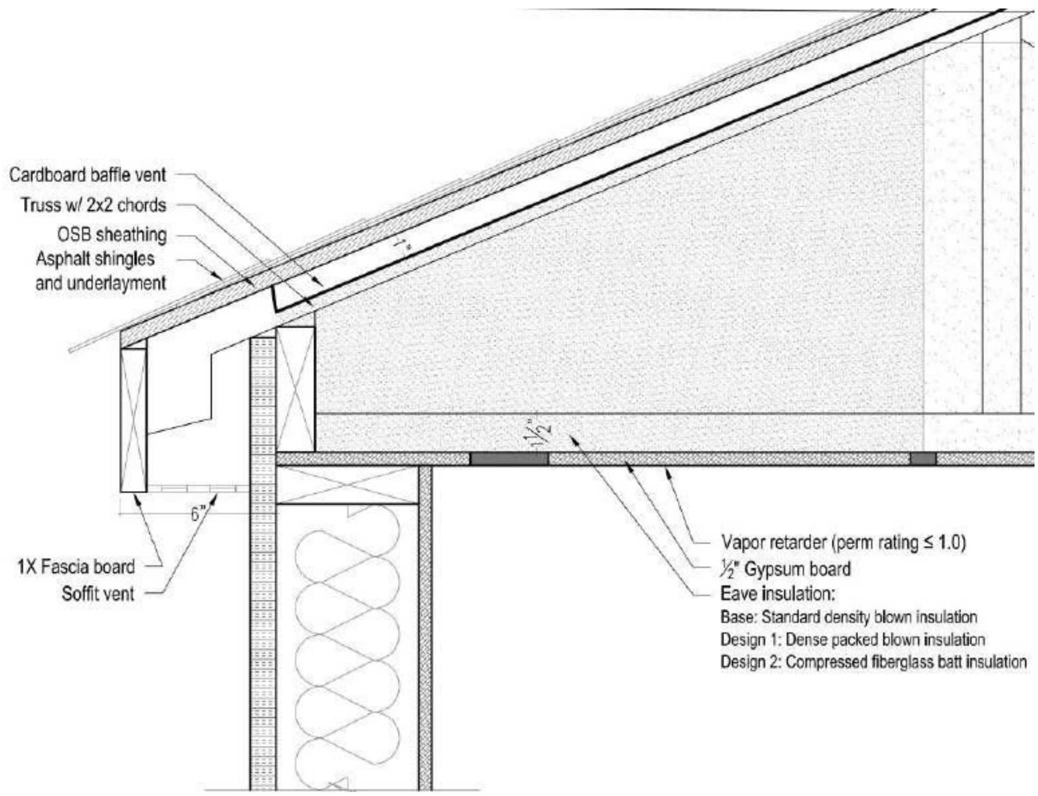


Source: The Levy Partnership, Inc.

A detailed description of the design and construction of the base case and the advanced roof design assemblies is provided below:

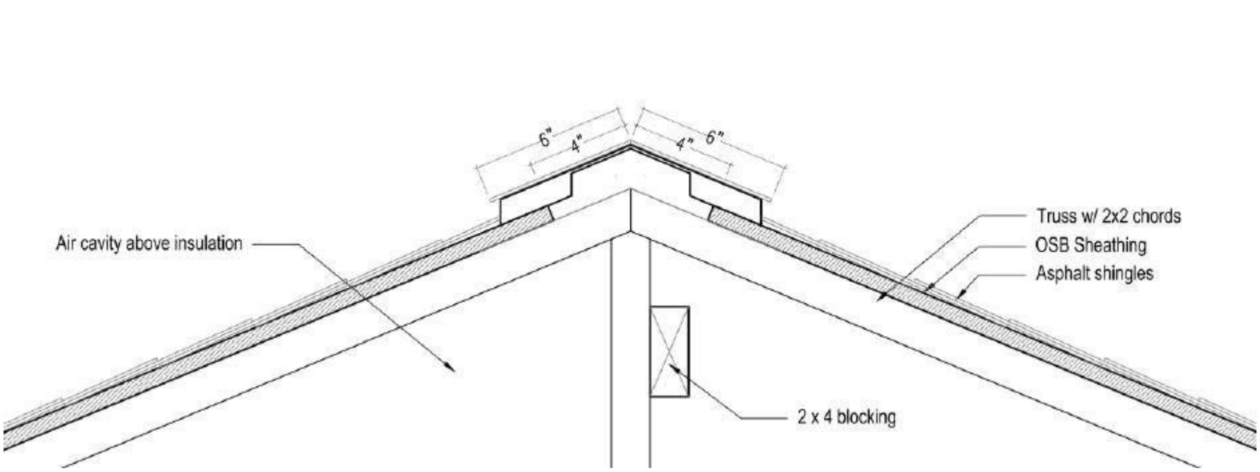
- Base design: Conventional roof construction with standard density blown insulation in the attic with baffles providing ventilation path (see Figure 63 and Figure 64).
- Design 1 - Vented attic roof with dense-packed insulation at eaves: Dense-packed/compressed blown insulation to increase the thermal performance at the eaves and standard density loose fill insulation at the center of the attic (see Figure 63 and Figure 64).
- Design 2 - Vented attic roof with compressed batts at eaves: Combines two types of insulation to achieve a more uniform U-value across the attic; blown/loose-fill insulation at the center with compressed, unfaced batt insulation at the eaves (see Figure 63 and Figure 64).

Figure 63: Typical Cross-Section at Eave - Base / Design 1 / Design 2



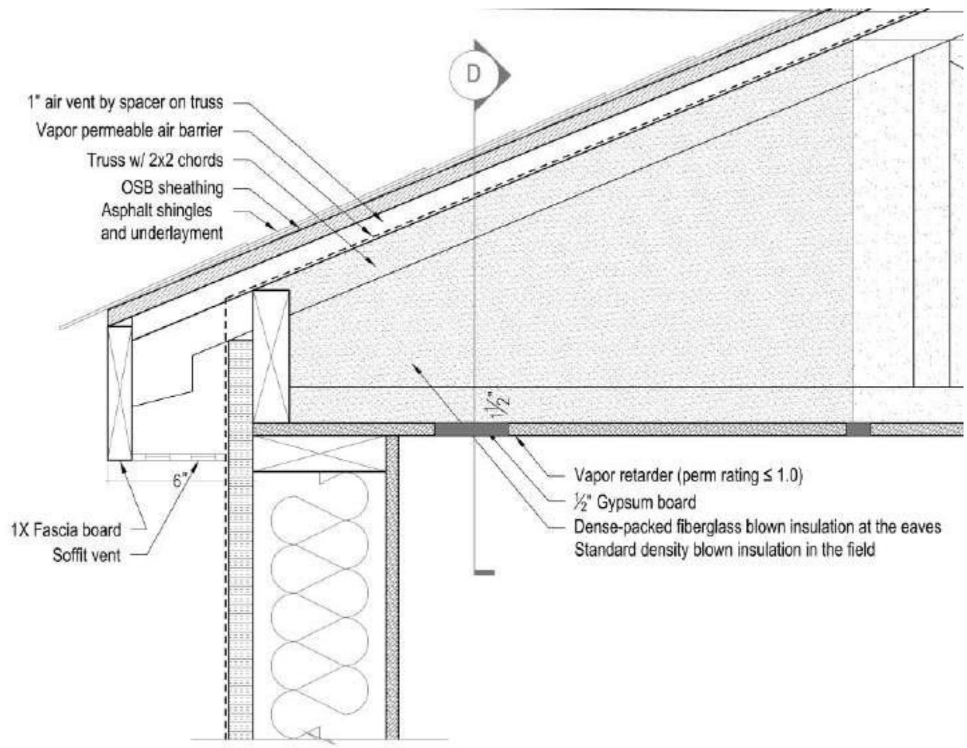
Source: The Levy Partnership, Inc.

Figure 64: Typical Cross-Section at Ridge - Base / Design 1 / Design 2



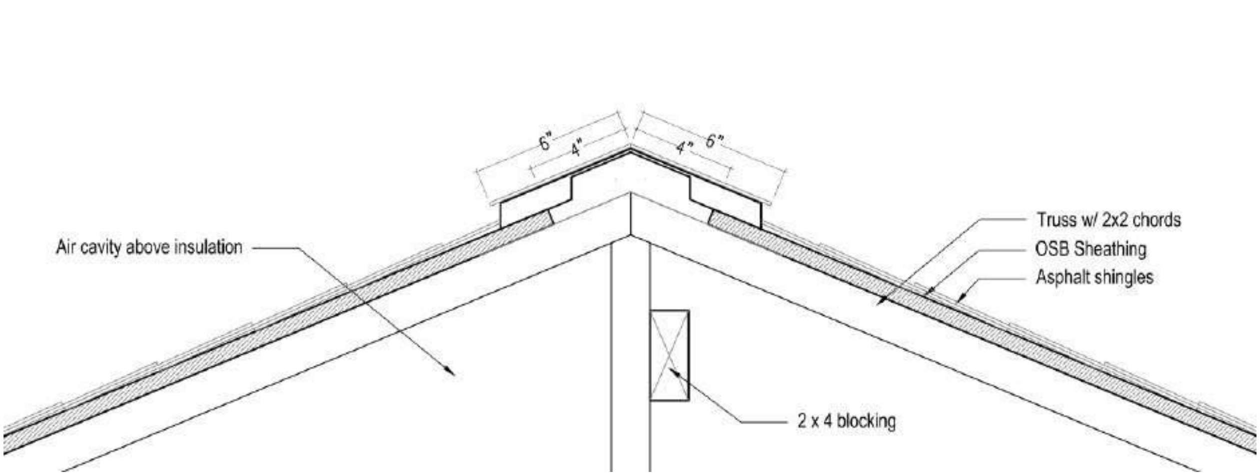
Source: The Levy Partnership, Inc.

Figure 65: Cross-Section at Eave - Design 3



Source: The Levy Partnership, Inc.

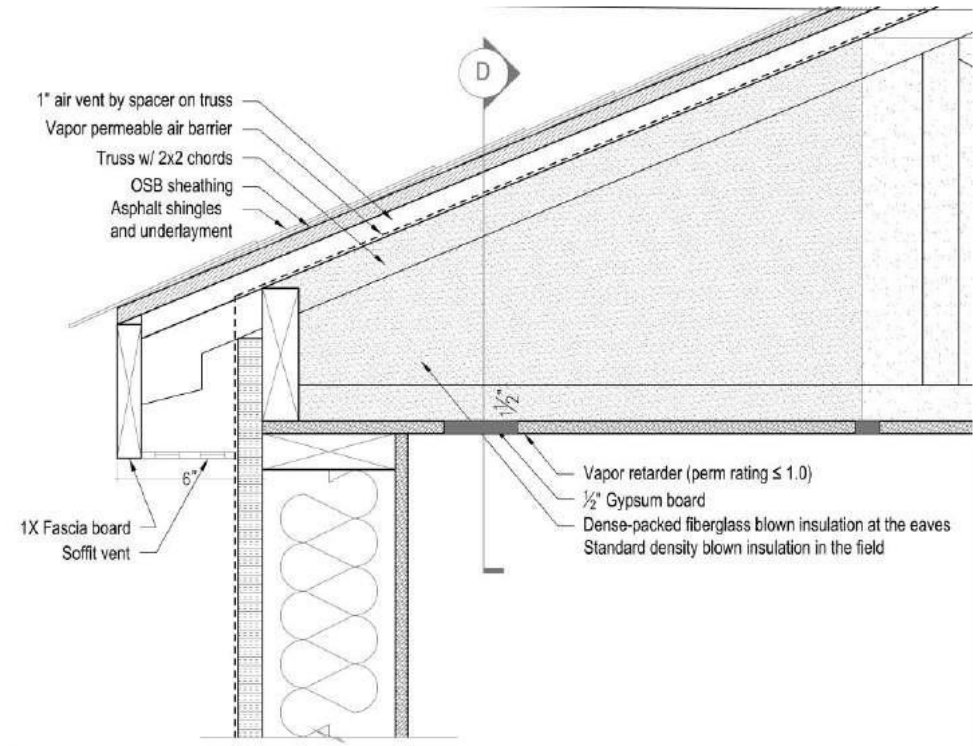
Figure 66: Typical Cross-Section at Ridge - Base / Design 1 / Design 2



Source: The Levy Partnership, Inc.

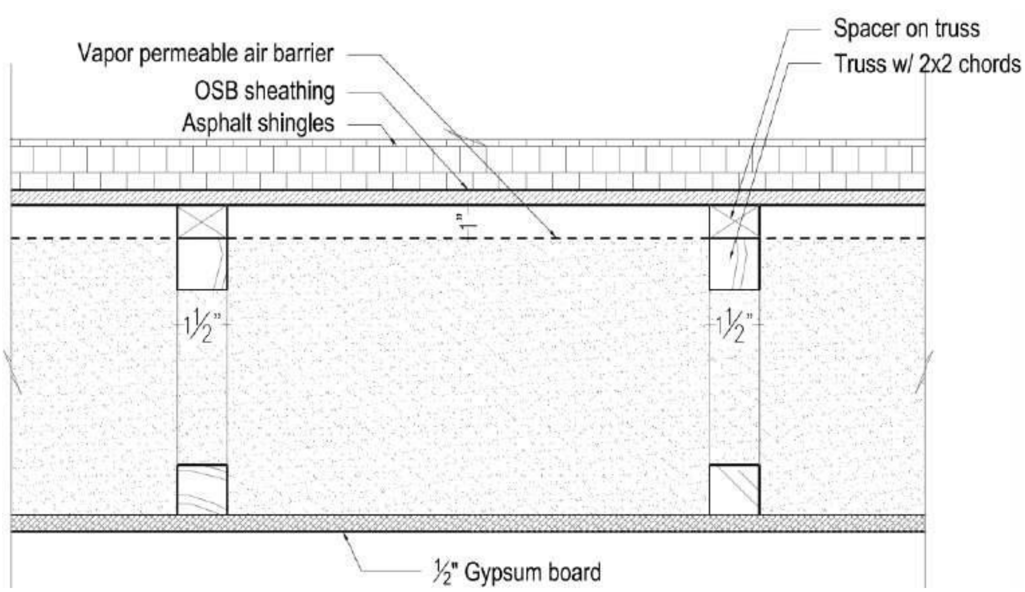
- Design 3 - Vented, sealed attic roof with dense-packed blown insulation at the eaves: Vented, sealed attic roof with dense-packed insulation at the eaves and standard density blown insulation in the field. An air barrier with high perm rating is used to seal the attic against any air movement/communication with the vented upper roof. This roof design, in particular, is being evaluated for impact on thermal performance due to the restriction on air movement by the air barrier.

Figure 67: Cross-Section at Eave - Design 3



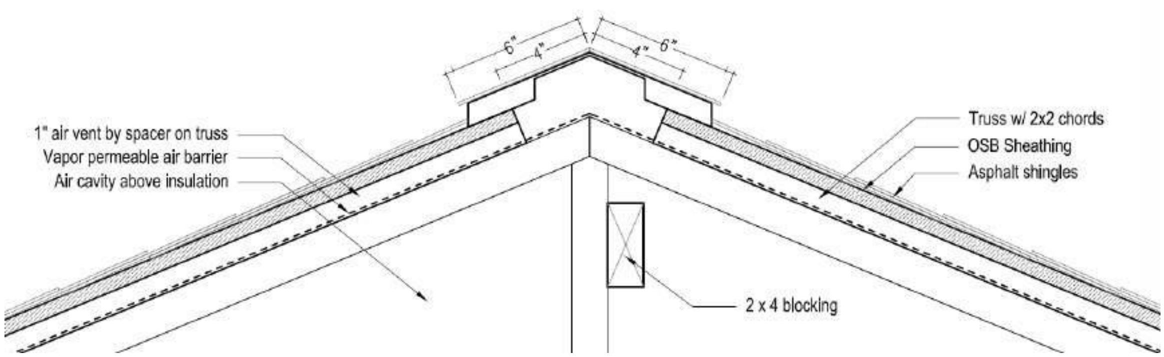
Source: The Levy Partnership, Inc.

Figure 68: Section at D



Source: The Levy Partnership, Inc.

Figure 69: Cross-Section at Ridge - Design 3



Source: The Levy Partnership, Inc.

The installation procedure of the air barrier is described below:

A vapor permeable air barrier membrane is installed between the 1" vent spacer and the truss. The membrane spans across the three truss bays and is attached to the top chord of a truss by means of adhesive. If staples are used to tack the membrane to the truss then the staples must be taped and sealed. The spacer is nailed to the truss through the air barrier layer.

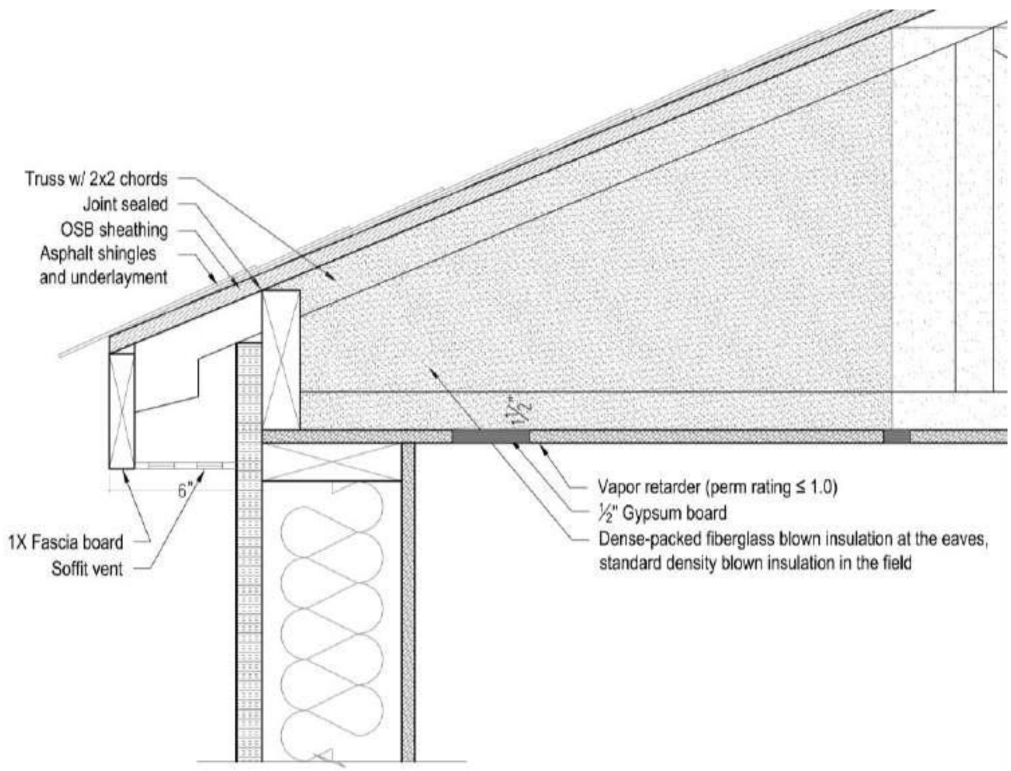
The air barrier membrane is wrapped around the sides and the eaves to effectively seal the roof cavity. At the edge of the roof bay the membrane is wrapped over the truss and taped to the side of the top chord. In addition, the length of the membrane along the slope is attached to the rigid XPS foam layer by means of adhesive or continuous bead of glue. At the eaves, the air barrier layer is wrapped over and the edges are taped to the wall rigid insulation. The siding is installed as per typical practice.

- Design 4 - Unvented, sealed attic roof with dense-packed blown insulation at the eaves: This roof option incorporates an unvented, sealed attic with dense-packed blown insulation at the eaves and standard density blown insulation in the field area. A diffusion vent (a vapor permeable air barrier vent) is used at the ridge that would allow the accumulated moisture to dry out via vapor diffusion while still acting as an effective air barrier that reduces heat loss.

  The components and installation procedure of the diffusion vent are described below:

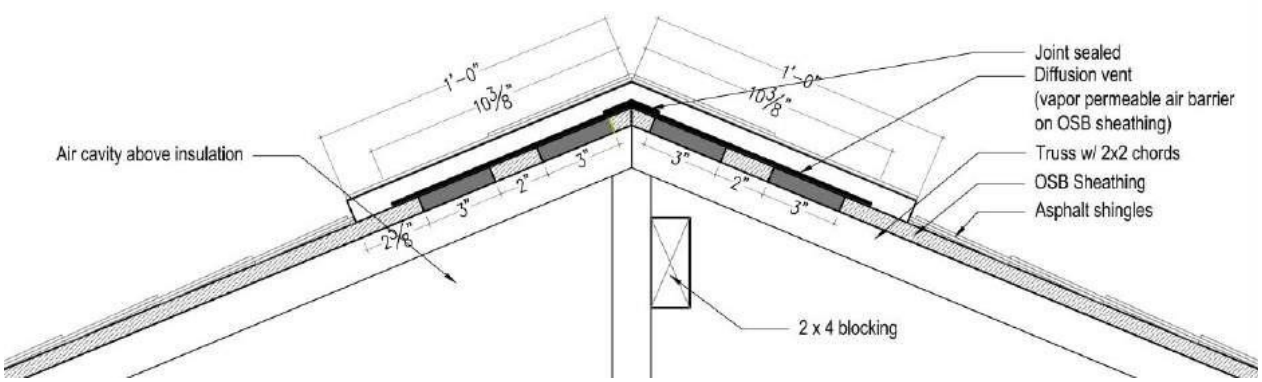
  A series of 3" diameter holes are drilled into the roof sheathing near the ridge of the truss bays. Holes should be drilled instead of omitting sheathing, due to the large area of the diffusion ports; a large opening would compromise on the structural stability of the roof during construction and provide no nailing base for the outer layers. The diffusion vent holes are covered with a layer of a vapor permeable air barrier membrane with a high perm rating (Tyvek house wrap).

Figure 70: Cross-Section at Eave - Design 4



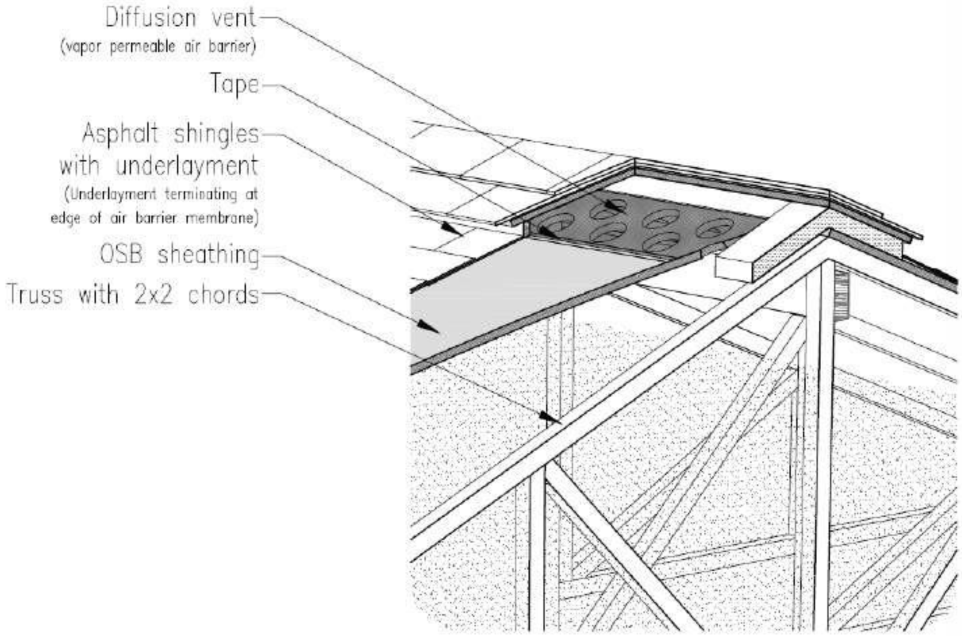
Source: The Levy Partnership, Inc.

Figure 71: Cross-Section at Ridge - Design 4



Source: The Levy Partnership, Inc.

Figure 72: Isometric View of Ridge in Design 4



Source: The Levy Partnership, Inc.

The edges of the air barrier membrane are taped to the roof OSB sheathing to seal the unvented roof cavity below. The edge of the roof underlayment is also taped to the edge of the air barrier membrane. The asphalt shingles are installed on the roof as per typical practice. The ridge is then covered with the typical attic ridge vent, which is in turn covered by sheathing and ridge cap shingles. See Figure 72 for an isometric view of the detail at the ridge.

Specifications and details of the manufactured housing unit planned for the prototyping and testing are listed in Table 15. The roof was subject to long-term monitoring and assessment with sensors installed to monitor temperature, pressure and humidity levels within the roof cavities, at possible condensation surfaces and in ventilation pathways. Interior humidity conditions were artificially introduced and the temperature inside controlled. Temperature and relative humidity set points were controlled remotely via a data logger. At the conclusion of the experiments the assemblies were disassembled and checked for any evidence of condensation, moisture accumulation or moisture-related damage.

Test Results, Analysis and Recommendations

One purpose of the roof component prototyping was to analyze the assembly process and consider issues that will arise in the plant when incorporating the designs into the factory production line. The prototyping process included elements of the construction process (for example, fastening, eave and ridge ventilation, and so on) that had the potential to slow production or adversely impact quality. The prototype also included the previously developed wall solution – framed walls with continuous exterior insulation. This section highlights the main findings of the prototyping effort.

Table 15: Prototype House Specifications

Specs	Base Design (inc. buffer)	Design 1	Design 2	Design 3	Design 4
ROOF CONSTRUCTION					
Roof design	Conventional roof	Vented attic roof with dense-packed insulation at eaves	Vented attic roof with compressed batts at eaves	Vented, sealed attic roof w/ dense-packed blown insulation at eaves	Unvented, sealed attic roof with dense-packed blown insulation at the eaves
Description	Conventional roof construction with standard density blown insulation.	Dense-packed blown insulation to increase the thermal performance at the eaves. Standard density loose fill insulation at the center of the attic. (See Appendix B for illustration of dense-packing blown insulation in attic eaves)	Combines two types of insulation to achieve a more uniform U-value across the attic; blown/loose-fill insulation at the center with compressed, unfaced batt insulation at the eaves.	Sealed attic roof with dense-packed insulation at the eaves and standard density blown insulation in the field. An air barrier with a high perm rating is used to seal the attic.	Sealed attic with dense-packed blown insulation at the eaves and standard density blown insulation in the field. Diffusion vent (a vapor permeable air barrier vent) used at the ridge to allow accumulated moisture to dry out via vapor diffusion while still acting as an air barrier.
Roof frame	Truss w 2x2 chords (spacing as specified in drawings). (see Appendix B)				
Attic insulation	Field: R-49 standard density blown FG† Eave: R-49 standard density blown FG†	Field: R-49 standard density blown FG† Eave: Dense-pack blown FG†	Field: R-49 standard density blown FG† Eave: R-38 compressed FG batts† (or approved alternative)	Field: R-49 standard density blown FG† Eave: Dense-pack blown FG†	Field: R-49 standard density blown FG† Eave: Dense-pack blown FG†)
Ventilation	Vented	Vented	Vented	Vented	Unvented
Ventilation type	Baffles†, ridge and soffit vents, end plugs at ridge vent	Baffles†, ridge and soffit vents, end plugs at ridge vent	Baffles†, ridge and soffit vents, end plugs at ridge vent	1.5” x 1” spacers on truss, ridge and soffit vents, end plugs at ridge vent	Ridge and soffit vents, end plugs at ridge vent *
Air barrier	n/a	n/a	n/a	Vapor permeable air membrane** around the roof truss cavity	Diffusion vent at the ridge. Vapor permeable air barrier**
Roof partitions	2” thick XPS rigid insulation† (2 layers of 1” thick with staggered seams)				

Specs	Base Design (inc. buffer)	Design 1	Design 2	Design 3	Design 4
Roof finish	Asphalt shingles with underlayment				
GENERAL CONSTRUCTION					
Exterior wall	Height: 7 ft. sidewalls Framing: 2" X 6"@ 16" o.c. Insulation: • R-21 FG batts in cavity† • R-5 exterior rigid foam insulation (XPS)† Wall underlayment: Building paper or typical practice for weather-tight barrier Interior finish: ½ " gypsum board with paint Exterior finish: Vinyl or hardboard siding				
Doors	Doors 1 and 2: Standard insulated manufactured home exterior door with locks				
Floor	Framing: 2x10 floor joists @ 16" o.c. or approved alternative Insulation: R-38 FG batts† (or approved alternative) between joists Floor finish: Linoleum on floor decking				
Air-tightness measures	The testing structure must be sealed against air leakage at all joints, seams, and penetrations associated with the building thermal envelope, including: • Taping all joints of the exterior continuous wall insulation; • Gaps and penetrations in the thermal envelope sealed with caulk, foam or gasket, or other suitable material; • Rough openings around exterior doors sealed with caulk or foam; • Sealing methods between dissimilar materials must allow for differential expansion and contraction; and, • Bottom plate sealed to floor decking and top plate sealed to the ceiling gypsum board.				
OTHER EQUIPMENT AND MATERIAL					
Mechanicals	Portable heat pump†				
Electrical	Portable lights, power bars and cables to provide electrical service and internet†				
Furniture	Tables and surfaces for testing equipment†				

† Item provided by TLP.

*** Design 4 is unvented but will be constructed with ridge and soffit vents.**

**** Air barrier membrane should have perm rating >10.**

The prototype construction of the advanced roof designs and the previously developed wall solution helped acquaint production staff with the assembly of the roof and wall solutions and begin to resolve issues that otherwise might slow production. Two major concerns arose during the roof prototyping with the potential to negatively impact plant flow: roof ventilation strategy at the eaves and the ridge and sealing the attic. The wall construction also presented two issues that had been previously identified: the use of tape at the panel seams and the method of cutting window and door openings.

This section discusses the construction of the test apparatus with a focus on the impact of the advanced roof and wall solutions on labor and time. Issues pertaining to general roof construction are discussed first while design-specific issues are addressed individually.

Because this prototype unit was intended for long-term testing the production details were more complicated and time-consuming than what would be otherwise expected in a typical production unit.

- Dense-packing blown insulation. Three out of the four advanced roof designs used dense- packed blown insulation at the eaves. Dense packing the eaves required constructing two dense-packer molds. Accurate design of the packer was critical to ensure it fit the geometry of the roof trusses and extended as far inwards as the target insulation levels required. Once the design was on paper, building the packer itself was straightforward. It was made from peg board and 2x lumber. Because of the varying truss spacing in the test unit, two dense- packers had to be built.

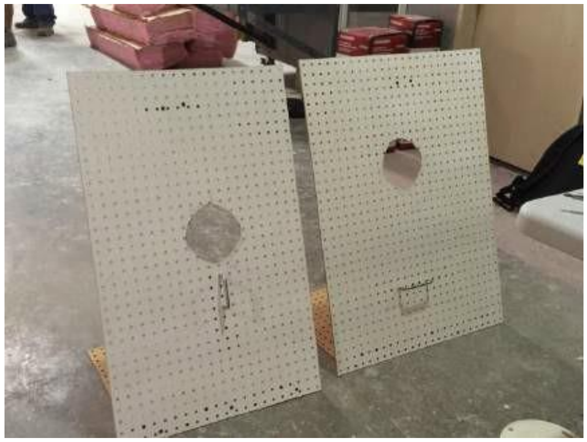
Figure 73: Bottom View of Dense Packer

Source: The Levy Partnership, Inc.

The piece on the floor is in the vertical position facing the attic field when in use. The 2x block connecting the two faces is cut to the required angle. These packers did not have sides because they would interfere with sensors; therefore a piece of wallboard was manually held in place at the sides to prevent insulation from spilling out to adjacent bays through the truss frame.

The first dense packing was conducted in a buffer bay where insulation density was not critical. It was found that the high pressure setting of the blower prevented proper densification. Once the blowing pressure had been reduced to the minimum available by the equipment, dense packing proceeded without difficulty.

Figure 74: Top View of Dense Packer



Source: The Levy Partnership, Inc.

Blown insulation from the buffer zones at the ends were removed and weighed to calculate the density at the dense-packed eave. Table 16 shows the density of the dense- packed region for the four buffer zones and their average compared to standard density blown insulation. The thermal performance of dense-packed insulation has been compared with the properties of blown-in-blanket system (BIBS) (as per manufacturer recommendations). The average density of the dense-packed blown insulation was 2 lb/ft^2 that yields R-4.21/in in the center of the region.

Table 16: Blown Insulation Density of Dense-Packed Eaves

Location	Weight (lb)	Volume (cuft)	Density (lb/cuft)
Buffer west by D4	4.8	4.25	1.13
Buffer west by Base Buffer east by Base Buffer east by D4	9.8	4.25	2.31
	7.7	4.25	1.81
	8.5	4.25	2.00
Average density of dense-packed eaves			2.04*
Manufacturer's spec for standard density (settled)			0.91
Manufacturer's spec for BIBS product (comparable to dense-packed insulation)			2.0

*** Does not include data for Buffer West by D4. It was the first bay to be dense-packed and the pressure was too high and kept blowing insulation out of the cavity. This reading was not reliable and thus excluded from the average.**

Source: The Levy Partnership, Inc.

A small one-time investment in time and labor is required to build the packer for standard truss dimensions and insulation packages. Dense packing the eaves requires an additional person to handle the packer, but is a quick application process. The design of the packer needs to be improved to overcome the lateral spillage.

Figure 75: Dense-Packing Application at Roof Eave

Source: The Levy Partnership, Inc.

Figure 76: Compressed Height of Batts at Eave

Source: The Levy Partnership, Inc.

Figure 77: Design 2 – Compressed Batts at Eaves

Source: The Levy Partnership, Inc.

- Compressing batts at eaves. Of the four advanced roof solutions, one design used compressed fiberglass batts at the eaves. R-38 fiberglass batts (typically 10.25" thick) were manually compressed at an approximate rate of 25 percent; i.e one and a half layers of batts were compressed to an average of 11" at the outer eave and two layers of batts were compressed to 16" at the inner eave. Because there is no direct way to know on site the compressed R- value at the eaves, this process needs to be refined further to get to the target insulation levels for standard envelope packages.

- Ventilation strategy at eaves. For roofs intended to be ventilated, the dense-packed insulation and compressed batts need to be held back in place by means of a baffle or other ventilation device.

  Baffles were used to create and maintain a 1" clear ventilation pathway at the eaves of designs 1 and 2 and the base case. Raft R-Mate baffles (manufactured by Owens Corning), used on the test apparatus, are designed to be fastened to the roof sheathing from below. Because in factory built housing the insulation is installed from above, the baffle also has to be installed from above. Therefore the baffles were trimmed to fit the truss bay and the side flanges were stapled down to the top chord. Traditionally manufactured homes use no baffles or cardboard baffles with side flanges scored and nailed to the truss. The prototyped technique is a significant variation, comparable in time and labor to cardboard baffles but more labor than having none at all.

Figure 78: Baffle Installation at Eaves

Source: The Levy Partnership, Inc.

Figure 79: Spacer Vent Installation in Design 3

Source: The Levy Partnership, Inc.

A 1” deep spacer vent was used in Design 3 (sealed attic with dense-packed eaves). The attic was first enclosed and sealed by means of a vapor permeable air barrier membrane (Tyvek HomeWrap), after which the spacers were nailed down to the truss top chord. Care was taken to avoid tearing the membrane. This design, as built in the prototype, adds labor and has the potential to delay the production process.

- Sealed attics. One of the advanced roof options calls for a sealed but vented attic. The attic was enclosed and sealed on the top and the sides by means of a vapor permeable air barrier. The membrane was adhered to the roof truss framework by means of adhesive and the edges were taped to the top plate at the sides. Taping at the corners and around the truss proved to be time-consuming; the membrane had to be split at the truss-top plate connection to maintain air barrier continuity. This process needs to be streamlined to be production ready.

Figure 80: Installing Air Barrier Membrane

Source: The Levy Partnership, Inc.

Figure 81: Taping Edges Around Truss

Source: The Levy Partnership, Inc.

- Ridge vent detail. Ridge construction was time-consuming because of the number of sensors. The ridge ventilation strategy for Designs 1, 2, 3 and the Base case used a standard ridge vent product .

  There was a variation for Design 4 that added labor and time to the process. Design 4 is unvented with a diffusion vent at the ridge. The diffusion vent was created by drilling three-inch diameter holes on the OSB along the ridge. A vapor permeable air barrier membrane (Tyvek HomeWrap) was overlaid on the holes to allow vapor to diffuse through. Since the typical ridge vents were not wide enough to cover the diffusion vents, a sheet exhaust vent (Cobra vent, manufactured by GAF) was used that could be modified to cover the entire vent area.

Figure 82: Installing Air Barrier Membrane on Design 4

Source: The Levy Partnership, Inc.

Figure 83: Ridge Vent Installation on Design 4

Source: The Levy Partnership, Inc.

- Isolating the roof designs. The partitions were thermally isolated from each other by means of two layers of 1" XPS foam insulation boards. Tape, foam, weatherstripping and caulk were used to prevent air movement between bays.

  Roof bays were isolated at the ridge vents from adjoining bays by means of 'Great Stuff' foam sealant.

Figure 84: XPS Foam Boards on One Side of Roof Truss (Typical)

Source: The Levy Partnership, Inc.

Figure 85: XPS Foam Boards Sandwiched between Two Roof Trusses

Source: The Levy Partnership, Inc.

Figure 86: Foam Sealant Application to Isolate Roof Vents from Each Other

Source: The Levy Partnership, Inc.

- Taping of seams at walls. Taping of the exterior continuous insulation seams during the prototype was a slow process. Application of the tape requires practice and discussion ensued with regard to the utility of commercially-available taping tools. The production team agreed that a better taping method is needed.

Figure 87: Taping of Seams at Walls

Source: The Levy Partnership, Inc.

- Tacking the foam boards. There is no precise method of ensuring that the recommended staples used to tack the exterior foam boards to the wall framing hit the studs consistently every time. This has been an issue with previous prototyping efforts and continues to be one. The technical team suggests that the foam board manufacturer print lines on the CI material that correspond to stud spacing.

- Cutting wall openings. The wall openings were cut twice, once for the foam and then for the siding. The continuous exterior insulation was cut by means of a rough-edge utility knife and then the fiber cement siding was cut by means of pneumatic scissors. The process, while adequate, was time consuming. This process needs streamlining to be production ready.

Evaluation

In general, dense packing roofs at the eaves offered a high performance roof solution that is fairly well-resolved with regard to construction detailing. The high density blown insulation provides enhanced thermal performance to the eaves which has traditionally been the weakest link of the roof performance. Once incorporated into the production line, dense packing may require an additional worker during the dense packing process but should not affect production line speed. Dense packing may be more easily accomplished in plants with catwalks that provide unimpeded access to the eaves.

The ventilation processes associated with the different roof designs present production complexities of varying degrees. Significant modifications to the assembly sequence and the production line can be seen in Designs 3 and 4. Design 3 also presents an additional challenge in sealing the attic. In the factory building environment where production speed is the principal determinant of profitability any changes, however small, to the production process can be important. The advanced roof solutions require worker training, careful execution and appropriate products.

Manufacturing Process Analysis

The manufacturing process was analyzed to develop a manufacturing strategy for roofs with dense-packed insulation at eave locations that, by stream lining production on the line, also reduces total cost. This was achieved by examining each production activity and eliminating any waste found. The task seeks to lower total cost in three ways: (1) reducing the cost of fabricating and assembling the advanced roof design; (2) reducing the cost of other production activities for the roof (such as reducing inventory and therefore storage related costs); and (3) leveraging these improvements to increase the overall plant production rate and reduce overhead.

This section presents analyses and evaluations of the manufacturing process of the advanced roof design in terms of safety, quality and producibility. The advanced roof solution was compared against the current construction process.

Baseline Process

The advanced roof technology is distinguished by dense-packing blown insulation in the area inboard of eaves to improve the overall thermal performance of the roof. The eaves of the manufactured housing roofs present constricted space for insulation and have traditionally been the weakest thermal point of roof construction. While dense packing blown insulation in this space will improve the thermal performance of the roof, it is expected to have an impact on the production line. It was determined that the impact would be limited to the roof insulation and decking station in the plant. This section focuses on characterizing the current manufacturing process of traditional roof construction with emphasis on the safety, quality and producibility of the roof solution. The advanced roof construction will be compared and assessed against the Baseline process to quantify its impact in terms of labor hours.

The baseline analysis focused on activities where the advanced roof design will likely have impact: roof insulation and decking station in the plant. Golden West Homes, Perris, California, is a subsidiary of Clayton Homes and was the industry partner for this study. The plant currently produces about 15 homes per week on a 2.5 hour cycle time. Plant staff indicated that the plant produces at much higher rates during periods of more robust sales. Line layout and movement is sidesaddle with lift trucks repositioning units along the line. Units of multi-section homes were clustered along the line by the home they belong to (i.e. Units A, B, and C to Run #100).

The plant builds both flat and cathedral ceilings. At the time of the visit, only one home on the line had a cathedral ceiling.

The plant currently uses blown cellulose as the standard attic roof insulation material although in the past blown fiberglass was standard. Fiberglass was substituted for the research home.

The current roof insulation process includes inserting a short strip of fiberglass batt at the eaves in each truss bay prior to blowing the cellulose. All roof insulation activities for a multi-unit home take place at the same stations on the line with no interruption for line movement. No catwalks are currently used. Roof access is by stepladder. Cellulose fiber is delivered by a mechanical blower with the hose capable of reaching all stations involved in roof insulation.[5]

The baseline (current) process was observed and documented on five units from three runs:

- Unit C, Model # GLE661L-SPL, Run # 120. An end unit of a three-unit manufactured home, approximately 13'6" wide x 64'8" long, with a flat ceiling and trusses spaced 24" on center. Unit analyzed on October 26th, 2016.
- Units A and B, Model #CK481F-SPL, Run #540. A two-unit manufactured home, units approximately 13'6" wide x 48'0" long, with a cathedral ceiling and trusses spaced 24" on center. Units analyzed on December 5, 2016.
- Units A and B, Model # GLE528F-SPL, Run #550. A two-unit manufactured home, units approximately 13'6" wide x 58'8" long, with a flat ceiling and trusses spaced 24" on center. Units analyzed on December 6, 2016.

Current Manufacturing Activities

[5] The plant previously used blown fiberglass for the attic insulation. The decision to move to cellulose was partly a corporate supply decision and partly predicated on the higher R-value per inch of cellulose compared to blown fiberglass. Cellulose, however, does not improve in R-value as density goes up, fiberglass does. This analysis considers whether the improvement in R-value with dense packing fiberglass translates into greater cost-effectiveness when compared to standard density cellulose.

Roof insulation consists of two tasks: installing fiberglass batt insulation at the eaves and installing blown cellulose insulation in the rest of the ceiling. The process includes:

- Rolling fiberglass batt insulation along the length of the eave.
- Using a utility knife, cut the batt insulation into small sections to fit into each truss bay.
- Applying adhesive in each truss bay at the eave and attach a pre-cut batt. Adhesive is carried in a one gallon can.
- Removing all miscellaneous items from the roof to prepare for blown insulation.
- Using a large diameter hose connected to a mechanical blower, spread cellulose material so that it covers the rest of the ceiling.

Current Manufacturing Performance

Safety

All roof insulation activities occur after roof set and are accomplished while walking on the trusses at roof height. Workers used a safety harness tethered to a line suspended along the factory ceiling to reduce injury in case of fall. Access to the roof was by ladders placed on the side of the unit. A bottom-level rung of the ladder was tied directly to the chassis to prevent the bottom from slipping out.

- Fiberglass batt installation: Batts were cut with a utility knife, but the task was performed safely with little risk of injury. The worker moved constantly on the trusses. The task required frequent bending (see Figure 79). No falls or unsafe actions were observed.

Figure 88: Installation of Batt and Blown Insulation

Source: The Levy Partnership, Inc.

- Blown cellulose installation: Although the worker worked on the trusses (see Figure 88), the blower broadcast the cellulose widely across the ceiling, and relatively little movement and no bending was required. No falls or unsafe actions were observed.

Quality

Batt insulation was installed to specifications in each truss bay at the eave (see Figure 90). Blown cellulose insulation was installed over the 9” level of the depth indicators in the ceiling. Insulation depth did not appear to be uniform, with some areas being closer to 8”, and some closer to 10”. Air flow at the eave of some truss bays appeared to be restricted by the blown cellulose installed over the batt (see Figure 89). No baffles were installed in the roof to maintain an air path for ventilation.

Figure 89: No Airspace at Eave Location

Source: The Levy Partnership, Inc.

Figure 90: Final Disposition of Blown Insulation

Source: The Levy Partnership, Inc.

Productivity and Flow

Two workers were observed installing roof insulation; one installing batts at the eave and the other blowing insulation over the ceiling. The pace of all insulation activities was brisk. Both workers appeared motivated and competent. There were no significant disruptions during the tasks. Roof insulation required only a small fraction of the overall cycle time at the related stations on the line. After completing the roof insulation tasks, both workers assisted other members of the roofing team, installing roof decking and roof paper. Table 17 indicates normalized cycle times and labor content observed on the 5 baseline units observed.

Table 17: Normalized Cycle Times and Labor Hours – Baseline Process

Activity	Average duration (minutes/unit)	Workers	Average labor (hours/unit)
Cut batts	5	1	0.089
Install batts	3	1	0.047
Clean-up	3	1	0.045
Install blown insulation	12	2	0.40
Total			**0.56**

Source: The Levy Partnership, Inc.

Indirect Activities

Cellulose insulation is received, transported, stored and staged near the blower. Insulation is delivered directly to the point of use by a flexible hose fed by a mechanical blower. Based on these handling methods, the current protocol for material handling and storage is very efficient.

The impact of switching from standard blown cellulose to standard density blown fiberglass will be primarily associated with additional time required to change set-up only. The plant production staff did not foresee any changes in the rate of blowing or the duration of the blowing operation.

Test Process

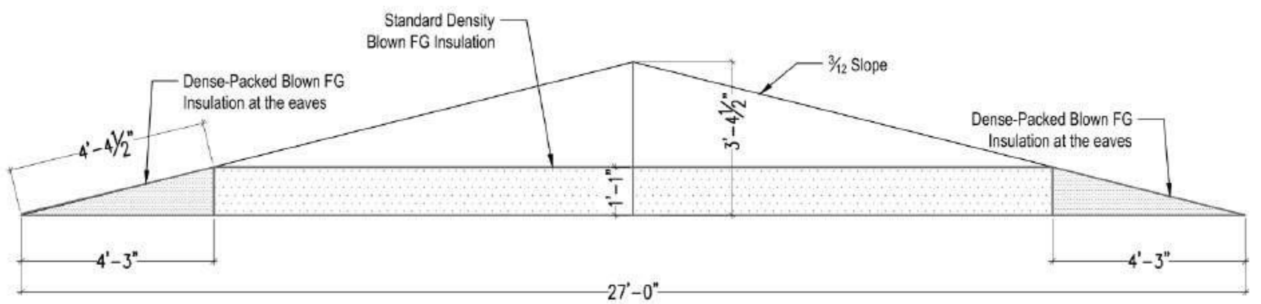
The advanced roof technology focuses on dense-packing blown insulation at the eaves to improve the thermal performance of the roof. The primary activities that will likely be impacted by the incorporation of this strategy pertain to the current roof insulation protocol. Below discussion on the advanced roof manufacturing process focuses on those activities only.

The advanced process was observed and documented on a multi-section manufactured home on the production line at the Golden West manufacturing facilities in Perris, California on December 6 and 7, 2016. The chosen home consisted of Units A and B, Model #CK601F-SPL, Run #560. It is a two-unit manufactured home; the units are approximately 13’6” wide x 48’0” long, with a flat ceiling and trusses spaced 24” on center. The unit was analyzed on December 7, 2016.

For the advanced manufacturing process demonstration, the plant used blown fiberglass as the insulation material for the roof. At the eave end, blown fiberglass was dense-packed for approximately 52" along the attic length of each truss bay. Fiberglass insulation was then blown over the rest of the ceiling to a depth of 13” for a target of R-38 in the attic center. To ensure air flow in the truss bays, cardboard baffles were installed over the insulation from the eave to the top of the dense-packed section, creating a one inch high unrestricted air pathway.

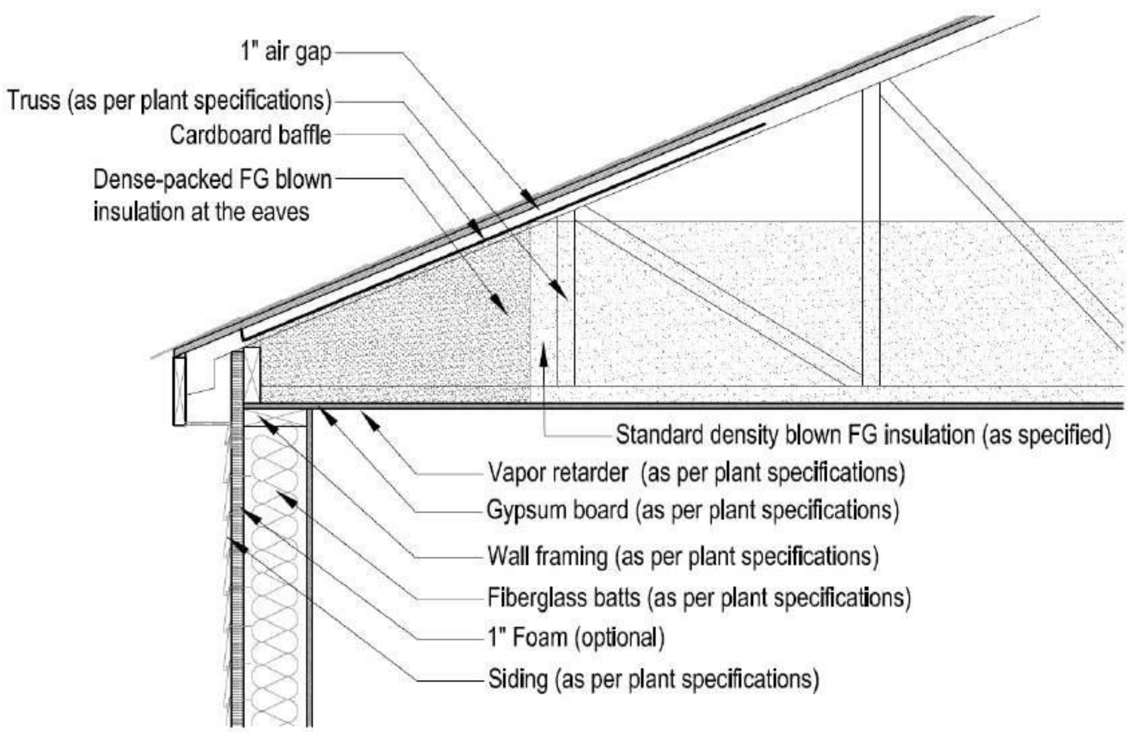
Figure 91 shows a schematic cross section of the advanced roof design of the prototype home and Figure 92 is a detail of the dense-packed region at the eave.

Figure 91: Advanced Roof Cross Section



Source: The Levy Partnership, Inc.

Figure 92: Detail of Dense-Packed Region at Eave



Source: The Levy Partnership, Inc.

Table 18 lists the specifications of the advanced roof design as compared with baseline construction.

Table 18: Advanced Roof Specifications

Specifications	Baseline construction	Advanced roof design
Roof design	Conventional roof	Vented attic roof with dense-packed insulation at eaves
Description	Conventional roof construction with standard density blown insulation.	Dense-packed blown FG insulation to increase the thermal performance at the eaves. Standard density loose fill insulation at the center of the attic.
Roof frame	Truss w 2x2 chords (spacing as specified in drawings).	
Attic insulation	Field: R-21 to R-28 standard density blown cellulose Density: 0.559 lb/ft^2 Eave: R-13 high-density batt FG	Field: R-38 standard density blown FG† Density: 0.559 lb/ft^2 Eave: Blown FG dense-packed to R-35† Density: 1.43 lb/ft^2
Ventilation	Vented	
Ventilation type	No baffles. Ventilation was provided by airspace provided at eave locations above fiberglass batts, ridge and soffit vents, end plugs at ridge vent	Cardboard baffles or other to provide 1" vent space under the sheathing †, ridge ventilation as per plant specifications
Air barrier	n/a	
Roof finish	Asphalt shingles with underlayment	

†Item provided by Johns-Manville Corporation.

Source: The Levy Partnership, Inc.

Advanced Roof Insulation Installation Activities

All roof insulation tasks were performed by the roof insulation crew after plumbing, electrical, and heating, ventilation, and air conditioning (HVAC) tasks were completed in the roof.

The molds used to install insulation were key elements of process tooling. Two molds were used for insulation installation; both are constructed of pegboard and are illustrated in Figure

One mold intended for mid-bays had two fill holes along the centerline of the pegboard, with the primary fill port located near the eave end of the mold, and a flange at the back end of the mold to limit blowout. The mold went through iterative changes throughout the process, where a flange located at the heel end of the mold and the supporting structure under the pegboard was removed to ease installation. The second mold intended for end-bays had no fill ports or flanges, and was used to fill from the back.

The general flow consisted of the following tasks: install baffles at eaves, install insulation at eaves, install baffles along rafters, and install insulation in field. Tasks were performed at various times by one to four workers working simultaneously. All tasks were performed on roof trusses except for installing baffles at eaves, which was performed on scaffolding.

Install baffles at eaves

- From the scaffolding, fold, position, and staple cardboard baffles (the side flap only) to top plate of roof and fold back to allow for dense-packing (see Figure 93).

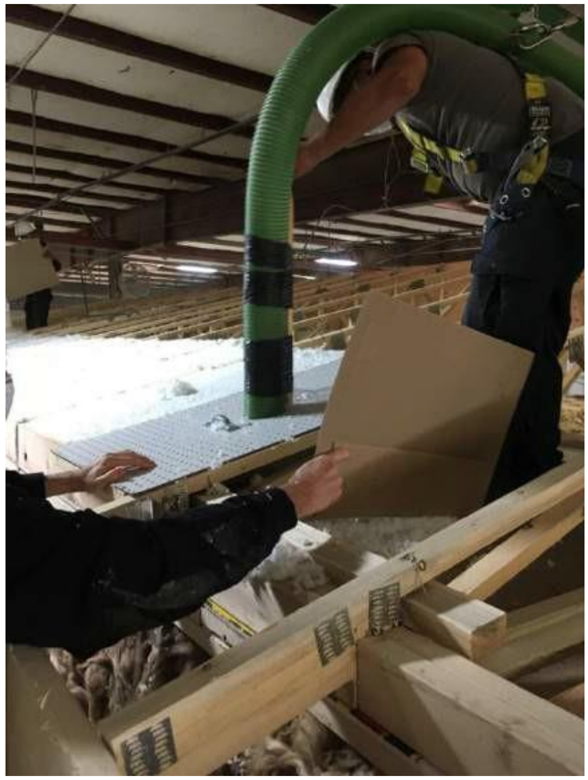
Figure 93: Installation of Baffles Prior to Dense-Packing

Source: The Levy Partnership, Inc.

Install insulation at eaves

- Position mold: One worker positions the mold over the truss bay to be filled during the cycle (seen on the right in Figure 95). The process starts at one end of the roof against a gable truss at the eave. Position the mold so that the back flange covers the end of the eave portion to be dense-packed. An extra baffle can be held at the side of the dense-packed area to prevent material blow-out on the sides. When the fill cycle is complete, move the mold to the next truss bays along the eave and continue the process.
- Fill mold: One worker positions the hose and fills the mold using the same delivery equipment used in the current method (see Figure 94). Two other workers are involved: one worker holds the baffle to prevent material blowout at the eave end, and another controls the insulation switch to start or stop the delivery equipment. Insert the hose in the primary fill port and run for approximately 30 seconds, or until the pegboard starts to bow. Direct the flow so the material is distributed evenly throughout the mold. Note that it is acceptable for some material to escape beyond the perimeter of the mold. This material may start to fill an empty area to be completed during a future cycle or fill voids/add density to areas filled during a previous cycle.
- If the mold cannot be used directly in the truss bays due to truss spacing or obstacles within the bay, the second mold without flanges will be used, and the bay will be filled from the back (see the left mold in Figure 86). Fill the mold with care to prevent blowouts.

Figure 94: Dense-Packing a Truss Bay



Source: The Levy Partnership, Inc.

Install baffles along rafters

- Fold down and staple cardboard baffles to the rafters in each truss bay up to the end of the dense-packed section. Two sizes of baffles were used during the build: a small baffle with dimensions 24" x 23", and a large baffle with dimensions 24" x 44". Configurations of baffles were either: 3 consecutive small baffles, 2 consecutive large baffles, or a combination of 1 small and 1 large baffle. Note that the insulation will need to be compressed during this process.

Install insulation in field

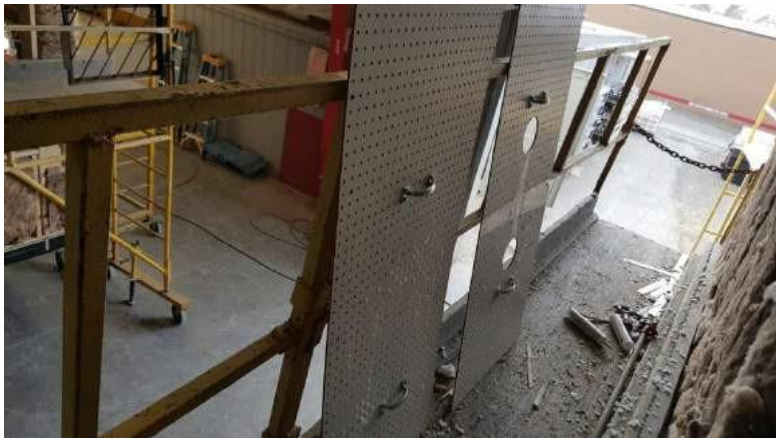
- Fill the rest of the roof with fiberglass insulation using the same delivery system. Note that this section of insulation is not dense-packed, but requires a greater depth than the baseline. The advanced home will require an insulation depth of 13" to achieve R-38.

Advanced Roof Predicted Manufacturing Performance

Safety

All roof insulation activities occurred after roof set, and were accomplished by walking on the trusses at roof height or walking along scaffolding adjacent to the unit. The fall arrest systems did not change from the baseline to advanced build; only workers who were walking on trusses wore harnesses. Access to the roof was by the scaffolding itself. The scaffolding was anchored to ensure it stayed in place during the build.

Figure 95: Top View of End-bay (left) and Mid-bay (right) Insulation Molds



Source: The Levy Partnership, Inc.

- Dense-packed eaves – Eaves were dense packed with three workers at the unit: two standing on roof trusses, and one standing on scaffolding. The worker on the roof controlling the insulation switch moved intermittently on the trusses and did not require any bending. The worker on the roof responsible for placing the jig and blowing insulation moved very often on the trusses, and this activity required the worker to stand in uncomfortable positions.

Figure 96: Staff Dense-Packing and Moving Insulation Mold

Source: The Levy Partnership, Inc.

- Blown fiberglass field installation – The blown fiberglass insulation in the field was not unlike that of cellulose in the baseline build. Although the worker worked on the trusses, the blower broadcast the fiberglass widely across the ceiling, and relatively little movement and no bending was required. No falls or unsafe actions were observed.

Construction staff at the plant noted that the use of the insulation mold on roof level made the process more unsafe than their baseline. Suggestions included insulating with the mold from scaffolding or using a mold that covers multiple eave bays at a time.

Quality

Blown fiberglass insulation was installed as stipulated in the test plan. Fiberglass insulation was dense-packed at each truss bay to a depth of 13”. A sample was used to determine the density of the dense-packed insulation and was calculated to be 1.43 lb/ft^2. Each truss bay was dense-packed to a satisfactory level, shown in Figure 97.

Figure 97: Dense-Packed Eaves

Source: The Levy Partnership, Inc.

Field insulation was installed over the 13” level of the depth indicators in the ceiling. Insulation depth appeared to be more uniform than the baseline build, but still had areas that were lower or higher than 13” on the depth indicators.

Baffles were installed in each truss bay up to the end of the dense-packed insulation to maintain an air path for ventilation. In all cases, the baffles accomplished this successfully. Baffles were required to be cut to size in truss bays smaller than the 24” off center, due to inconsistencies in roof construction. Figure 98 shows the dense-packed insulation with baffles installed.

Productivity and Flow

A maximum of four workers were observed installing roof insulation.

One worker affixed cardboard baffles at the eave end to limit material blowout at the eave. Dense-packing fiberglass insulation at the eaves was an unprecedented activity that required four workers: one was responsible for placing insulation into the blower to distribute it to the line; a second was responsible for placing the mold in the eave bay, holding the mold in place, and blowing the insulation into the mold; another worker was responsible for controlling the blower switch; and the last worker was responsible for keeping insulation on the roof on the eave side using the pre-attached baffles.

Figure 98: Baffles Installed over Dense-Packed Fiberglass Insulation

Source: The Levy Partnership, Inc.

Other activities that deviated from standard construction were less intense and handled easily by the plant staff. One worker was responsible for installing the baffles along the rafters following dense-packing, and removing/positioning excess cardboard material that could have hindered the installation of roof sheathing. Two workers were responsible for installing the field insulation, one on the roof level, and one at the blower.

Table 19 indicates cycle times and labor content observed on the advanced roof.

Table 19: Cycle Time and Labor Hours – Advanced Roof

Activity	Duration (minutes/unit)	Workers	Labor hours/unit
Fix baffles	16	1	0.27
Dense-pack eaves	38	4	2.50
Install baffles	61	1	1.02
Install field insulation	30	1	0.50
Total			**3.66**

Source: The Levy Partnership, Inc.

The pace of all insulation activities was brisk. The workers appeared motivated and competent. There were a few significant disruptions during the tasks:

- Learning process: A period of troubleshooting and revision occurred during the first several dense-pack fills in order to find the quickest and easiest way to dense-pack the eaves to a sufficient level. This included a period where the insulation mold was modified for a better fit within the truss bays (shown in Figure 99 and Figure 100). This would not be a significant disruption if this was a regular process.

Figure 99: Removing Eave Flange and Substructure from Dense-Packer Mold

Source: The Levy Partnership, Inc.

Figure 100: Modified Dense-Packer Mold in Place

Source: The Levy Partnership, Inc.

- Baffle incompatibility: The baffles used were for truss bays of 24" on center. However, some of the bays were either slightly bigger, or slightly smaller by fractions of an inch. This required modifying the baffles to either cut them to size (if bay is slightly too small) or determine an alternative installation method (if bay is slightly too big); this time disruption becomes more pronounced when the baffles are larger and become harder to modify.

Indirect Activities

The standard blown cellulose used at Golden West Homes was switched to blown fiberglass insulation. The impact of this switch was associated with additional time for set-up only. The plant construction staff did not change the rate of blown insulation.

Analysis of Observed Performance

Based on observed manufacturing performance, it is clear that the advanced method of roof insulation is not yet ready for production use. Safety is not enhanced over the baseline; the task is physically more taxing and requires frequent movement and bending. Labor content is higher than the current method, resulting in increased labor cost and extended cycle times. This would limit production capacity unless the insulation delivery system is expanded. However, the quality of blown insulation largely met expectations: the density of the eaves resulted in 1.43 lb/ft^2, close to the predicted density of 1.50 lb/ft^2.

Several enhancements to the advanced method were suggested during a meeting between the research team and the Golden West installation crew:

- Create a safer insulation strategy that would allow staff to insulate from catwalks or scaffolding rather than roof trusses. This can have a positive effect on both safety and productivity.
- Use baffles that are easier to work with or do not require as laborious of an installation. The shorter (23”) cardboard baffles were notably easier to install, and modify (when required) than the longer (44”) baffles.
- Relocating insulation switch to the hose itself to allow for one employee to control blowing and place the hose, rather than two.
- Mold design changes:
- Use flexible flanges to adapt to different truss bay widths, depths, obstructions within the bay (plumbing, electrical, mechanical, and so on), and prevent side blowouts. Flanges might be made of narrow strips of flexible but heavy material.
- Use a mold which covers multiple bays at a time, lessening the time required to lift and place mold in next bay.
- Add light frame superstructure or straps to minimize bending while lifting and moving the insulation mold.

In conclusion, the advanced roof design with dense-packed eaves offers a solution that is thermally more efficient than the baseline construction, but with added labor cost. The analyses and evaluations in this section indicate additional labor hours primarily attributed to the learning curve involved. The dense-packing process is an innovation that the manufactured housing industry is not accustomed to. Experience gained during this prototype build and study will be helpful in informing continued research on next steps that could focus on streamlining the manufacturing process of advanced roofs. It is expected that a creative and well-vetted solution will minimize the incremental labor cost significantly.

Full-Scale Prototyping

Full-scale prototype testing of dense-packed cathedral roofs and stud walls with exterior continuous insulation (CI) was conducted on May 18-19, 2015 in association with partner manufacturing plant, Skyline Homes, Inc. (Woodland, California). The blown FG insulation prototyped and tested was Propink L77, manufactured by Owens Corning. The exterior continuous insulation board tested was FOAMULAR® 250 XPS, also manufactured by Owens Corning. Participating in or present for the test were members of the Technical Steering Committee, Energy Commission Project Manager and the The Levi Partnership technical team. Skyline management and plant staff collaborated on the planning, helped formulate the manufacturing plan and were instrumental in resolving production problems as they arose.

Test Plan

The advanced roof design being prototyped is a vented cathedral roof with dense-packed blown, fiberglass insulation at the eaves/sloped roof cavity and standard density loose fill insulation in the center of the roof. Dense-packing blown fiberglass insulation increases the thermal performance at the eaves in attic roofs (reduces heat loss), which has, traditionally, been one of the weakest link in the building thermal envelope. In cathedral systems, the advanced roof design aims at increasing the thermal performance along the roof profile by dense-packing the truss cavity.

Figure 101: Advanced Roof Design – Vented Attic Roof with Dense-Packed Blown Insulation at Eaves

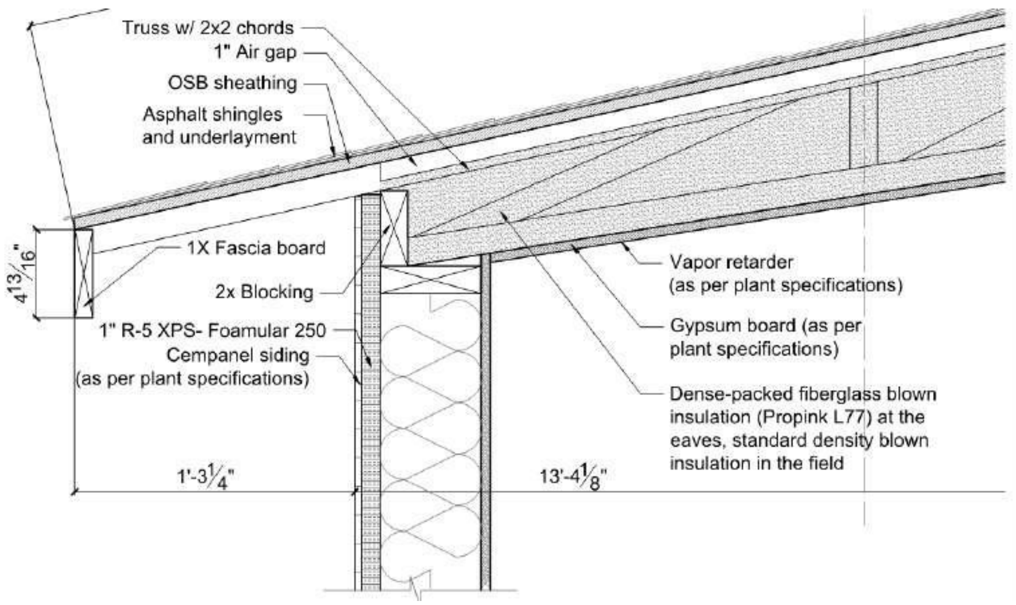
Source: The Levy Partnership, Inc.

Construction Details

The manufactured home selected for the whole-house prototype build was a double-section unit measuring 56’ x 28’ with a cathedral roof at a slope of 2.7/12. This section focuses on the construction details incorporated during the prototype demonstration of the advanced roof design. Details of the advanced wall design have been covered in previous sections.

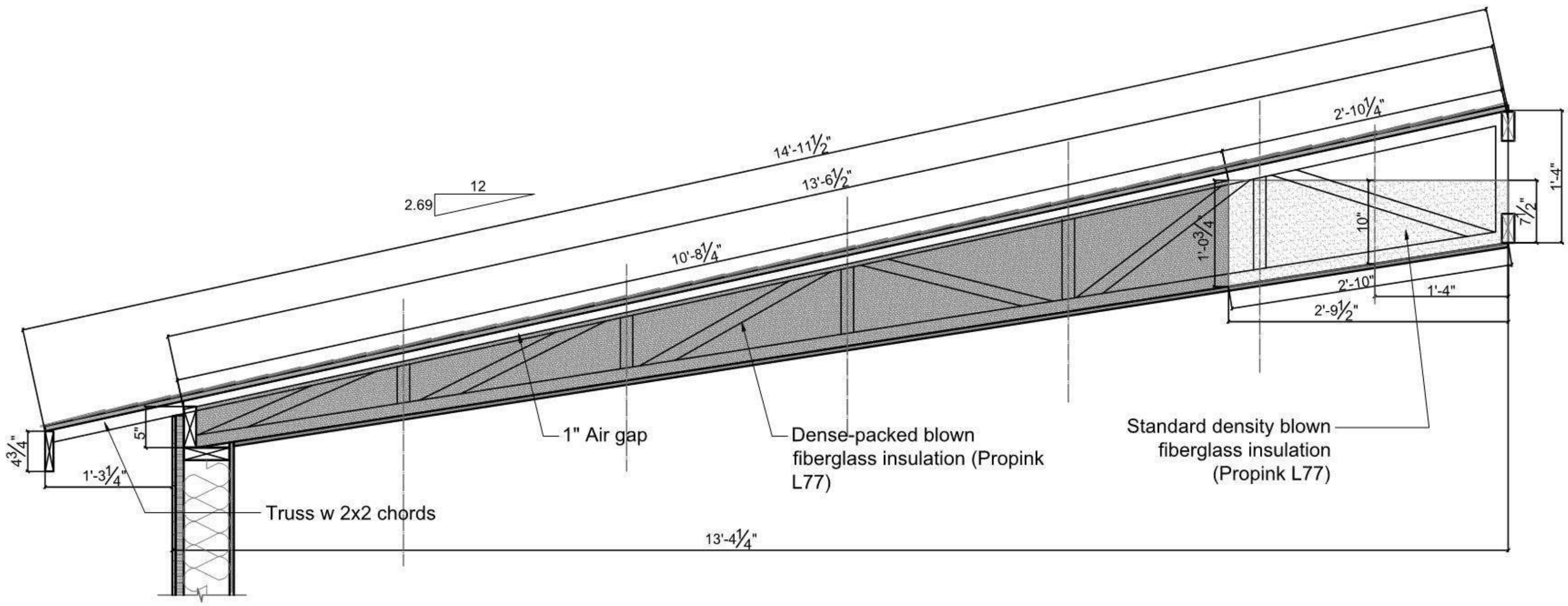
Figure 102 shows the construction detail at the eave of the advanced roof design and Figure 103Figure 94 shows the extent of dense-pack insulation in the cavity. A 1” air gap under the sheathing was accomplished through the use of prefabricated cardboard baffles.

Figure 102: Advanced Roof Design (Cathedral Roof) – Detail at Eave



Source: The Levy Partnership, Inc.

Figure 103: Advanced Roof Design (Cathedral Roof) – Cross Section



Source: The Levy Partnership, Inc.

Detailed Specifications

Table 20 provides detailed specifications on the advanced wall and roof designs. The unit will be built as per plant manufacturer specifications with a few changes to the wall and roof assemblies as noted in the table.

Table 20: Detailed Specifications for Wall and Roof Assemblies

Item	Specifications
ROOF CONSTRUCTION	
Roof design	Vented cathedral roof with dense-packed insulation at eaves/in the roof cavity
Description	Dense-pack blown insulation in the roof cavity to increase the thermal performance of the roof. Appendix B shows the planned configuration of dense-packed insulation and standard insulation in the roof cavity. The extent of dense-packing was established in accordance with the NFA (net free area) limits required for mechanical ventilation at the roof peak. (See Appendix B for illustration of dense-packing blown insulation in attic eaves)
Roof frame	As per plant specifications
Cavity insulation	Dense-packed (in the sloped roof cavity) @ R-4.26/in; density – 1.5 lbs./cu. ft.. R-value at the heel (5”) – R-21.3 R-value at the highest depth (12.75”) – R-54.3 Standard density (at the center): @ R-3/in; density (estimated) – 0.52 lbs./cu. ft.. R-value at the highest depth (12.75”) – R-38.25 R-value at the roof center (7.5”) – R-22.5
Ventilation	As per plant specifications - mechanical ventilation (VentilAire IV System) at the gable end; 1” air gap along the roof slope by means of cardboard baffles
Air barrier / Vapor retarder	As per plant specifications
Roof finish	As per plant specifications
EXTERIOR WALL CONSTRUCTION	
Wall design	Stud walls with continuous exterior insulation
Description	Continuous exterior rigid insulation to increase the thermal performance of the wall system; (See Appendix B for wall construction details with continuous exterior foam insulation, and Appendix B for images on exterior foam installation)
Wall framing	2 x 6 @ 16” / 24” o.c. (spacing as per plant specifications)
Frame cavity insulation	R-21 HD EcoTouch Pink Fiberglass batts
Exterior continuous insulation	1” R-5 Foamular F250 XPS board
Wall underlayment, interior finish, exterior finish	As built
DOORS & WINDOWS	
Type	As built
Construction	See Appendix B for construction detail at window frame (to accommodate the 1” XPS)

Source: The Levy Partnership, Inc.

Product Characteristics

Table 21 describes the key materials subject to testing and evaluation.

Table 21: Physical Properties

Item	Property
WALL EXTERIOR CONTINUOUS INSULATION	
Insulation brand name	Foamular® 250
Insulation type	Extruded polystyrene rigid foam or XPS
Manufacturer	Owens Corning
Product thick. @ R-5	1”
Perm rating @1”	Class III (1.5 perm)
Compressive strength	25 psi
Integrated water and air barrier	Yes, with Joint SealR tape
Shear resistance	Not significant
Strengths	Can be cut with a saw, hot wire or scored and snapped Zero ozone depletion potential indicating negligible degradation to the ozone layer Maintains at least 90% of its R-value over the lifetime of the product and covers all ASTM C578 properties Contains minimum 20% recycled content
Limitations	Non-structural
Weight	0.13 psf for 1”
Available panel sizes	96” x 16”or 24” or 48” 108” x 48”
ROOF CAVITY INSULATION	
Insulation brand name	ProPink L77
Insulation type	Loose fill fiberglass insulation
Manufacturer	Owens Corning
Standard installed density (estimated)	0.52 lbs./cu. ft.
Dense-packed installed density	1.5 lbs./cu. ft.
Available bag size	33 lbs./bag

Source: The Levy Partnership, Inc.

Table 22: Product Data and Approvals

Item	Test type
Foamular 250	Product data sheet (http://www.foamular.com/assets/0/144/172/174/11b5f50a-0f80- 4f08-bebe-71f4b6a9fdf7.pdf) ICC ES Report ESR-1061 (http://www.icc-es.org/reports/pdf_files/SBC/ESR-1061.pdf) Meets ASTM C578 Type IV (Std. for rigid polystyrene insulation) (http://foamular.com/assets/0/144/172/174/068b3c93-7431-43c4-8d43- 53e09ea0b584.pdf) UL Classified ASTM E2178-03 (air permeance) NFPA 285 (fire tested wall assemblies)
ProPink L77	Product data sheet (http://insulation.owenscorning.com/assets/0/428/429/440/9f5a9d05-9916-434a-90f5- dfba4c04bc8c.pdf) Manufacturer's fact sheet (http://insulation.owenscorning.com/assets/0/428/429/431/a62e0dba-0753-4159-ad19- b99518b67cda.pdf)

Source: The Levy Partnership, Inc.

Material Needs and Sources

Table 23 on the following page lists the material requirements for the advanced roof and wall assemblies and their sources.

Observations and Evaluation

In general, the dense-packed cathedral roof solution posed several issues during the roof insulation installation process on the production line. The dense-packed attic roof solution was modified to be incorporated for the entire cathedral roof, an application type that had not been attempted before. Dense-packing the cathedral roof proved difficult and the developed template did not work satisfactorily (the template has been successful during prior demonstrations for attic roofs). There were numerous issues like excessive material blow-outs, voids to fill, inconsistency in installed density, and so on. The issues encountered suggest the need for additional testing and evaluation.

The use of CI on stud walls (in this case, Owens Corning's FOAMULAR® 250 XPS insulation board and related products) offered a solution that is fairly well-resolved with regard to construction detailing and product application. The installation process went smoothly with minimal additional labor and the foam panels provide a continuous insulation layer that is durable, virtually eliminates thermal bridging, and can be installed in the plant with little training. Application of the tape to the joints enabled the material to also serve as an air and water resistive barrier, providing potential cost savings by eliminating the need for a separate material to serve this function. In general, CI is ready for widespread commercial use although the product, for the most part, is not used by and not familiar to the manufactured housing industry.

The focus of this section is on the advanced roof insulation installation process in comparison to the standard roof build/installation process. Observations and items that require further analysis and development are also described below.

Table 23: Material Needs and Sources

Product brand name/code	Description	Quantity*	Supplier
INSULATION MATERIALS			
Foamular 250	XPS 1" thick; 4' x 8' panels	65 panels	Owens Corning
Propink L77	Blown fiberglass attic insulation	72 bags (33lbs./bag)	Owens Corning
TAPES			
Joint SealR tape	To seal the seams and edges of the continuous exterior insulation	11 rolls @ 90' each	Owens Corning
Flash SealR tape	Flashing tape around the window and door openings	4 rolls @ 90' each	Owens Corning
LUMBER			
2x2 blocking	Extra blocking needed around door/window openings to accommodate 2" thick exterior insulation	As needed	--
FASTENERS			
Senco 2" x 1" crown 16 gauge staple (P21BAB)	Insulation staple	--	Senco
Senco 3" x 0.120 RS Nail (H627ASBX)	Siding nail	--	Senco
16 gauge, 1" wide crown, 2" heavy wire stapler (WC200 XP)	Staple gun	1	Senco
4" 34 clipped head framing nailer (SN951XP)	Nailing gun	1	Senco
DENSE-PACKER MOLD			
Peg board	Material required to fabricate the dense-packer	--	--
Angle-blocking		--	--
Handle		4	--
Nails/screws		--	--

*** All quantities based off home size – 56' x 28'.**

Source: The Levy Partnership, Inc.

The advanced roof solution incorporated dense-packed blown fiberglass to insulate the roof of the test house. The test house was a double-wide design with each unit measuring 13' 4" x 56'.

The design incorporated a cathedral roof with trusses on 16" center. To assure air flow in the low, narrow truss bays, cardboard baffles were installed over the insulation from the eave to the ridge of each bay, creating a one inch high air pathway. The design also included a dormer over the main entry on the front unit. The dormer roof was insulated with R-21 compressed fiberglass batts. While research was conducted on both roof sections of the house, to simplify this study only one unit was used in the comparative analysis discussed in this report.

The method originally proposed for installing the dense-packed blown fiberglass had been successfully employed in another factory, although in a more limited application - only at the eaves on a flat attic ceiling. This method incorporated a 16" x 5' 4" pegboard mold with a flange on each end to limit material blowout. The mold was placed in each truss bay and filled through a fill port using the existing insulation delivery system.

Observation

All roof insulation tasks were performed by the roof insulation crew after plumbing, electrical, and HVAC activities had been completed in the roof. The mold used to install dense-packed insulation was a key element of process tooling and the design of this equipment underwent several iterative changes to streamline the installation process.

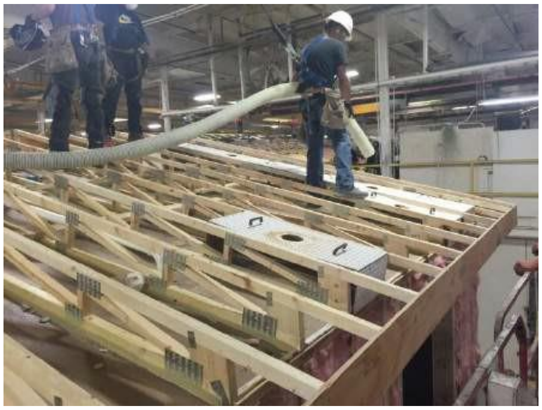
The initial mold constructed was designed to cover one truss bay and up to a pre-determined length (see Figure 104). Several of these were constructed to cover the entire slope of one truss profile (see Figure 105). These initial molds had two flanges – a shorter one at the bottom end and a longer one at the rear to prevent blow-outs (insulation leaking out of the sides of the trusses) on either ends.

Figure 104: Initial Mold Design

Source: The Levy Partnership, Inc.

However, the first few runs quickly showed significant blow-outs on the sides which led to the improvisation of the mold to include side flanges as well. This second iteration of the mold design resulted in a box-like structure (see Figure 106). This mold was unsuccessful as well with the blown FG pressurized to occupy the restricted space inside. As a result, the insulation remained within the mold upon removal of the latter from the truss (see Figure 107). The technical team and construction crew discussed reasons for failure and identified one possibility attributed to the rough interior surface of the peg board. The team went back to the construction table to redesign the mold.

Figure 105: Single-Truss Span Molds Set Along Slope of Roof



Source: The Levy Partnership, Inc.

Figure 106: Improvising Single Truss Mold with Side Flanges

Source: The Levy Partnership, Inc.

Figure 107: Unsuccessful Attempt at Dense-Packing with Enclosed Mold

Source: The Levy Partnership, Inc.

The subsequent design of the mold had the peg-board used inside-out to reduce frictional resistance between the insulation and the mold. This design was wider and spread over two trusses during one cycle installation. One fill port was provided towards the center with one rear flange to limit back flow and two shorter side flanges (see Figure 108).

Figure 108: Wider Version of Mold Redesigned to Reduce Friction and Cycle Time

Source: The Levy Partnership, Inc.

Figure 109: 2-Truss Span Mold Design in Use

Source: The Levy Partnership, Inc.

The final mold design consisted of a 4' x 8' sheet of pegboard with a pegboard flange extending at a 90 degree angle from the bottom of one end to limit material blowout. The flange was notched to accommodate four trusses when the mold was positioned lengthwise over three truss bays to be filled during a cycle. Two fill ports were provided along the long centerline of the mold. The primary fill port was located approximately two feet from the flanged end. A secondary fill port was located approximately three feet further along the axis.

Figure 110: Final Mold Design

Source: The Levy Partnership, Inc.

The general flow consisted of the following tasks – install baffles at eave, install insulation (except ridge), install baffles (except eave and ridge), install insulation at ridge, and install baffles at ridge. All tasks can be performed by one worker working independently, except for the installation of insulation (except ridge), which requires at least two workers. All tasks were performed while standing on the trusses, except install baffles at eave, which can be performed from the catwalk.

- Install baffles at eave: From a catwalk, fold, position and staple a corrugated baffle in each bay at the eave.
- Install insulation (except ridge):
    - Position mold: The mold is positioned by two workers over three truss bays to be filled during the cycle (see Figure 111). The process starts at one end of the roof against a gable truss and at the eave. The mold is located so that the flange covers the end of the eave baffles. When the fill cycle is complete, it is moved to the next three truss bays along the eave and this process is continued until the entire eave section of the roof is complete. The mold is then lifted, rotated 180 degrees and moved up the truss bays until the remaining upper area of the roof is covered.
    - Fill mold: One worker fills the mold using the same equipment used in the current method (see Figure 112). The blower feed rate is reduced to a minimum to lessen material blowouts. The hose is inserted in the primary fill port and allowed to run for approximately 55 seconds. The flow of the material is directed so that it is distributed uniformly throughout the three truss bays covered by the mold and excessive blowouts are minimized. The second worker assists during the fill process,

attempting to minimize any excessive blowouts when they occur by covering the affected area with a small form (OSB) and cleaning up excess materials. Note that it is acceptable for some material to escape beyond the perimeter of the mold. This material may start to fill an empty area to be completed during a future cycle or fill voids/add density to areas filled during a previous cycle. When filling the mold on the upper section of the roof, the secondary fill port is also utilized. This port is located to fill voids remaining between the eave fill and the upper section fill through the primary fill port.

- The mold could not be used directly in all truss bays due to truss spacing and obstacles within the bay (plumbing, wiring, fans, ducts, and so on). For these situations, it is inverted (flange side up) and filled with care to prevent blowouts.

Figure 111: Two workers Position Mold over Three Truss Bays on Test House

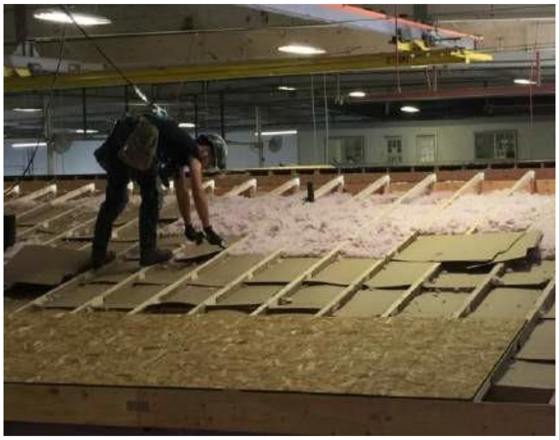
Source: The Levy Partnership, Inc.

Figure 112: Worker Installs Blown Fiberglass Insulation through Secondary Fill Port of Mold on Test House

Source: The Levy Partnership, Inc.

- Install baffles (except eave and ridge): Five baffles are folded, positioned and stapled in each truss bay so that they leave a one inch gap for airflow on top of the insulation (see Figure 113). Note that the insulation will need to be compressed during this process.

Figure 113: Worker Installs Corrugated Baffles between Eave and Ridge of Roof on Test House



Source: The Levy Partnership, Inc.

- Install insulation at the ridge: Using a mold, the ridge is filled parallel to the roofline; the insulation is compressed to the desired shape (parallel to the floor); and a corrugated baffle is installed to assure air flow over the insulation.
    - The mold is positioned over three truss bays to be filled during the cycle. The process starts at the ridge on one end of the roof against a gable truss. When the fill cycle is complete, it is moved to the next three truss bays along the ridge and this process is continued until the entire ridge section of the roof is complete. Note that a smaller, simplified mold approximately 4' x 3' without a flange is used.

Figure 114: Baffle Installation

Source: The Levy Partnership, Inc.

    - The mold is filled using the same equipment as that used in the current method. Fill time is reduced proportionally (about 30 seconds).

- Baffles are installed at the ridge.
- The insulation in each truss bay at the ridge is compressed to the desired shape leaving enough room for the mechanical ventilation system within the attic (parallel to the floor) using a small piece of pegboard.
- Baffles are folded, positioned and stapled in each truss bay.

Analysis

Safety

All insulation tasks were performed while standing on the trusses, except installing baffles at eave, which was performed from the catwalk. All tasks required frequent movement and bending. Workers used a safety harness tethered to a line suspended from the factory roof. No falls or other mishaps were observed.

The advanced method involves more opportunity for injury than the current method. Most tasks are performed while standing on trusses and movement is frequent and often involves bending. The extent of injury from a fall can be limited by the use of a safety harness.

Quality

The research team reviewed the quality of the insulation installation on the second unit (rear) of the test home. Voids were observed under several eave baffles. Low fill levels were observed at various locations on the roof. In addition, there were several reasons to question the uniformity of the fill density.

- There was noticeable variation in surface texture, ranging from flat and uniform (see Figure 107) to "fluffy". This suggests differences in the fill density.
- Hand compression of insulation at various locations suggested loose fill.
- Weight checks performed on the first day on the first unit (front) of the test house during process refinement indicated wide variation in installed material weight, even when using the same method. Weight checks were not performed on the second day for the second unit (rear) of the test house, which used a more consistent, refined method of installation. The research team decided that further disruption on the main line was not advisable.

Productivity and flow

The research team observed much of the work on the second unit (rear) of the test house. The team did not observe a considerable part of the install insulation (except ridge) task, which began before the team arrived on site on the second day. The team was able to observe three cycles of this task, and the performance was consistent with the total time and manpower reported by the Skyline installation crew.

The pace of all operations was reasonable for testing a new process. There were no significant disruptions. Table 24 indicates estimated cycle times and labor content for the second unit (rear) of the test house. The advanced method requires about seven labor hours, seven times the labor required for the current method. It also requires two workers for the installation of insulation (except ridge) task.

All insulation activity cycle times were well within the line cycle time of four hours (two units per day) and could accommodate a line rate up to four units per day without adding equipment. Note that the current method allows up to 16 units per day without adding blowing equipment.

Table 24: Estimated Cycle Time and Labor Content for Rear Unit of Test House

Activity	Duration (Min/Unit)	Workers	Labor Hours/Unit
Install baffles at eave	25	1	0.4
Install insulation (except ridge)	118	2	3.9
Install baffles (except eave and ridge)	77	1	1.3
Install insulation at ridge	47	1	0.8
Install baffles at ridge	36	1	0.6
Total			**7.0**

Source: The Levy Partnership, Inc.

Evaluation

The proposed advanced method did not work satisfactorily for the test house. There were excessive material blowouts into adjacent truss bays and at the ends of the mold. There were also voids in the fill. Differing surface textures of installed insulation suggested varying densities. Removing and weighing installed material confirmed this suspicion. Several potential causes for the unsatisfactory performance were identified as below:

- Truss spacing: The trusses were spaced at 16" on center leaving very little width to dense-pack
- Fill length: The fill length was 5' as opposed to the previous installations of 2' long; this made it difficult to maneuver the blowing equipment to reach the far out spaces and maintain equal density throughout.
- Ceiling configuration: The ceiling configuration probably had a big role to play in the entire effort. The dense-packing procedure had been a success with attic roofs; it was the first attempt at incorporating the process for cathedral roofs. The shallow depth of the roof system probably led to the significant back-fires during the blowing procedure which led to the voids at the fill ports. Secondly this also led to the spillages on the sides that did not have immediate barriers.
- Blowing equipment: The blowing machine used for dense-packing fiberglass insulation is designed to blow cellulose insulation. While both are used for insulating roofs in manufactured homes, cellulose and fiberglass have different standard densities that yield different R-values. There was discussion that the blower, feed rate and delivery hose were not ideal for the installation of FG insulation.

- Worker technique: The construction crew at Skyline had no prior experience with dense-packing insulation material and was introduced to this concept on the first day of the build. There was a learning curve involved in the execution of this concept while trying to improvise the process and tools simultaneously. There were a number of prohibitive factors here that may have contributed to the unsuccessful process encountered at Skyline.
- Insulation type: While it is speculative, there was discussion of the possibility that the insulation material type (pink vs. white blown fiberglass insulation) contributed to the inconsistencies in the blown density. It should also be noted that the technical team has had success with the pink fiberglass insulation with several prior attic installations.

Regardless of the cause, it was clear that the proposed method was not sufficiently robust to handle these sources of variation.

To complete the test home, the research team and the Skyline installation crew attempted a series of modifications to the proposed method. As discussed above, alternate mold concepts were designed, fabricated and tested on the test house. One concept eliminated the mold entirely by installing the baffles first and using them as the mold. Differing fill rates and times were attempted. Different worker blowing techniques were tried. The first unit (front) of the test house was completed on the first day of testing using a variety of these modified methods. At the end of the first day, the process improvement effort was abandoned so that the test house could be completed without further line disruption. Finally, a larger mold spanning three bays was developed which worked better than others. On the second day of testing, the installation crew used this mold to finalize the method and complete the installation.

Results

The advanced wall construction involving the installation of continuous exterior insulation on the walls was a success. The plant had the right tools and fasteners and incremental time and labor involved in this process was minimal.

The advanced roof insulation process for cathedral roofs, however, was not found to be ready for production use based on the observed manufacturing performance. Safety is not enhanced by the extended labor content and the need to move frequently on the trusses. Repeated bending is also required. The extent of injury from a fall can be mitigated with the use of a safety harness. Quality is suspect given the observed voids and variation in fill level. There is also reason to believe that fill density is lower than specified and highly variable. Labor content is much higher than the current method, resulting in higher labor cost and extended cycle times. The latter will limit production capacity unless the insulation delivery system is expanded.

Recommendations

Further development of the advanced roof design will require process refinement. This effort must address tooling, delivery equipment, timing and worker technique. Proposed methods must be assessed for safety, quality, ease of use, labor and line flow. Installed fill density and consistency should be measured. Proposed methods must be robust, capable of handling the wide range of design configurations likely to be produced. Ideal applications should be identified, as well as any limitations where other alternatives (dense fiberglass batt, deeper blown cellulose) might work better. Finally, process testing should be performed off-line when possible, not on the main production line during regular production hours.

Several possible enhancements to the advanced method for cathedral roofs were discussed by the research team and the Skyline installation crew:

- Install baffles at the eave using the current method at the roof build and roof set stations.
- Use longer baffles between the eave and the ridge baffles.
- Fill the ridge area as part of the second stage fill, rather than a separate third stage.
- Mold redesign.
- Use flexible flanges to adapt to different truss bay widths, depths and obstructions within the bay (plumbing, wiring, vent fans, ducts). Flanges might be made of narrow strips of flexible but heavy material.
- Add a light frame superstructure or straps to minimize bending while lifting.
- Add a short flange under one end to get material under the eave baffle.

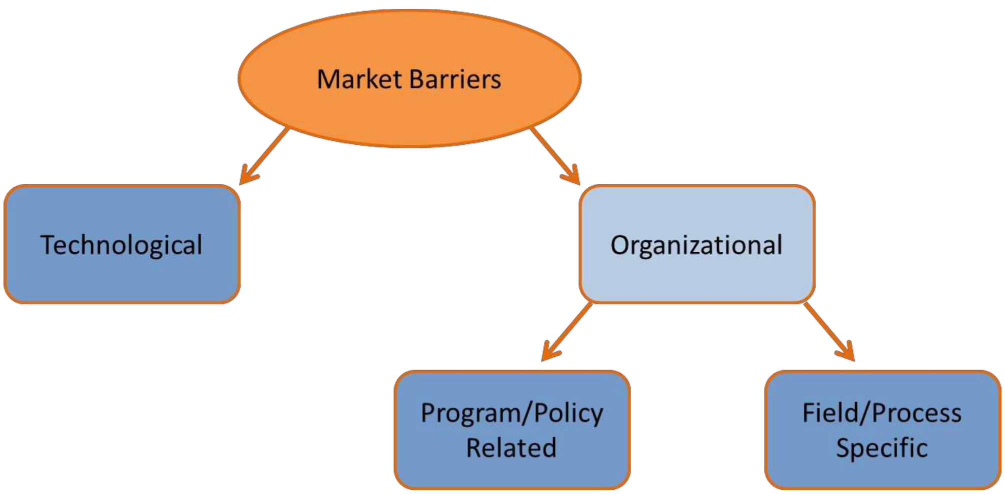
CHAPTER 5: Code and Market Evaluation

Research into energy-saving envelope technologies is insufficient on its own; the technology must be adopted and desired by both the industry and the consumer to effect meaningful and sustainable change in market behavior. This section identifies and addresses key market barriers to: a) energy-saving building strategies that go above and beyond code requirements; and, b) this project's proposed envelope systems in particular:

- Dense-packed roof eave insulation,
- Continuous, rigid insulation on exterior walls, and
- Cool roof strategies.

Market barriers can come in many forms (Figure 115), including technological (such as lack of technological readiness in relation to the production methods), process-related (communication and motivation deficiencies between agencies of the industry), and policy-related (codes, programs, and incentives missing the mark for the builder, manufacturer, and/or buyer.

Figure 115: Types of Market Barriers



Source: The Levy Partnership, Inc.

To better understand market barriers associated with this research, home manufacturers, retailers, marketing staff, and incentives-program implementers were surveyed with respect to their views on and stumbling blocks to implementing the technologies in question. The results from the information attained in these meetings were used to form a basis for overcoming barriers to market adoption, as well as a starting point for formulating an approach to production-readiness and outreach activities

Addressing Market Barriers

Once barriers to market acceptance are identified, they can be individually addressed from a variety of angles, depending on the type and source of the hurdle. A technological challenge in the plant, for example, can be best addressed by identifying the required processes, materials and tools a builder would need to effectively and efficiently implement the new strategy. On the other hand, a policy-related barrier may be a program that offers incentives to builders but not to home retailers, meaning an availability of energy-efficient homes without the legwork to sell them. The discussions that follow describe the principal barriers that are likely to be faced in implementing the technologies developed though the project and provide suggestions for their resolution.

Technological Barriers

Several technological barriers stand in the way of widespread adoption of the energy measures developed through this research effort. These are discussed below. For each barrier listed, a potential solution is suggested for further exploration in the future.

Warranty for Product Applications

- Obstacle: With new ways of applying existing although often unfamiliar products, product manufacturers may not warrant an intended use. Specific to this research, the producers of some common types of siding allow their use only when applied over no more than 1" of non- structural sheathing material, such as foam insulation. Restrictions like these may require product testing by material manufacturers and development of fastening specifications that address the structural issues involved. This hurdle will be addressed as part of the normal business development cycle.
- Recommended action: Accumulate structural and durability test results from this and other research on the application of rigid foam on manufactured home walls. Ensure that various attachment methods are explored and documented in order to create application specifications for rigid-foam suppliers to use. Promoting and sharing such research will open doors to home manufacturers, who may then more confidently provide quality manufactured homes while assuming less risk and offering a sounder envelope option, thermally and hygrothermally.

Increased structural loads

- Obstacle: Manufactured homes are exposed to more unpredictable conditions, and overall stronger forces, than are site-built homes. For example, highway transport often exposes homes to forces approximating earthquake forces. Industry sources in the state noted that, as they generally rely on adhering fiber cement panel siding to the exterior wall framing to provide shear strength, adding a thick layer of foam sheathing between these layers creates structural concerns and potential issues with factory assembly. Rigid siding has a tendency, when placed over non-structural sheathing, to come delaminate during the move from one station to the next, compromising component strength.

- Recommended action: One approach that provides adequate shear strength to a wall with foam board is adding structural sheathing (OSB, for instance) so that one is not relying on the siding for structural integrity. Further, the siding is properly fastened to the wall through the rigid board. Several methods have been proposed to accomplish this and the best approach depends on the type of siding, possibly in combination with furring strips. Most solutions require longer staples for fastening.

Product Availability

- Obstacle: As is often the case with new technologies their adoption is slow due to poor product availability. For instance, "cool roof" technologies are widely available, but sufficient research and/or consumer literature is often unavailable to support the products. And such information may be incomplete or misleading. For example, it is not uncommon for individual roof shingle products to offer energy savings based on general research, but finding corresponding products that have the desired reflectivity may require filtering through opaque technical literature, and the products may not be readily available.

  From a manufacturing perspective, some products may not be user friendly. For example, rigid- foam boards are generally sold in limited standard lengths and widths, sizes that cater to the DIY community or site builders. While exterior-wall height can vary from factory to factory, in general, the foam products that work on the production line are currently special sizes demanding a premium in price and are of limited availability. This will change as industry adopts the technology, but the initial higher cost presents a market hurdle.

- Recommended action: Limited product availability is a major barrier, but as codes change, the value of products like foam insulative sheathing and reflective roof finishes become more attractive and work their way into common practice. The current work could help make inroads in this regard, but sharing results with United States HUD and United States DOE, the federal agencies that together set the standards for energy performance of manufactured homes, is also necessary in widely distributing the pertinent information. If the standards provide credit for technologies like cool roofs, based on the value demonstrated by this research, manufacturers will be drawn toward products to meet these standards, which in turn will drive product availability.

  When asked about the barriers they face in adopting the use of exterior rigid insulation, one manufacturer noted that the product should be offered in nine-foot lengths (as opposed to eight-foot lengths) so that it could be simply laid side-by-side on their traditional nine-foot walls. Perhaps the first vendor to offer a competitive nine-foot rigid-foam product will transform the market, similar to how Roxul mineral-wool insulation has found its niche in residential application of ultra-high-density cavity insulation simply by offering products whose dimensions match those of residential building (Vardera, 2014). Additionally, research such as that performed in this project could be publicized and made available to customers and retailers, which may boost the market for high-performance insulation and roofing products and similarly drive product availability.

Equipment and Tool Availability

- Obstacle: Limited use of a technology may be more the result of a lack of proper tools or methods or installation or assembly, as opposed to the availability of the product. Dense- packing roof insulation, for instance, requires the use of fiberglass instead of cellulose – both widely available products, but products that use different insulation-blowing machines or equipment settings based on the properties of the insulation material. While cellulose could, theoretically, be dense-packed, studies have shown that cellulose does not increase in R-value with increased density. Fiberglass does. At standard densities, blown cellulose is thermally more efficient than blown fiberglass, but when dense-packed, the overall R-value of the roof is higher with blown fiberglass. Many Clayton plants recently switched from blown fiberglass to blown cellulose insulation for product-partnering reasons, meaning that their equipment is not currently configured for fiberglass and therefore cannot be used for dense-packing. Further, dense-packing requires the use of a "mold" to ensure that the target R value is achieved. Molds are a new tool, not currently used by the homebuilding factories. There is scope to further improve and develop the current mold design to make it more efficient.

  Representatives of the Clayton Perris plant also raised issues with the use of rigid foam on the exterior walls. With increased wall thickness, they may need deeper door jambs in addition to longer staples and stapling guns to handle the larger fasteners. Also, the windows would need to be installed with their frame sitting on the rigid insulation which would impact their structural strength, especially posing a problem in climate zones with high wind loads. These are all addressable issues that accompany any new technology but are important details undergirding the effective transfer of these new energy measures.

- Recommended action: The primary barrier in this case is the product partnering and product preference by the corporate office of the home manufacturer. When asked about demonstration builds, Clayton Perris and Hallmark stated that they would simply need to change the blower settings, as long as the insulation product was provided. However, this will slow production unless the plant switches fully to the next technology. Thus, a manufacturer wanting to use dense-packing in its roofs would likely want to return to using blown fiberglass only. For plants to commit to changing from cellulose to fiberglass insulation, convincing data on the effectiveness of dense-packed fiberglass will need to be distributed, and a marketing strategy (as will be addressed in future reports) will need to accompany the effort. Together these steps will help create demand for the technology. For example, the marketing strategy should point out that dense-packing vaulted and cathedral roofs may be beneficial in decreasing overall U-value that would otherwise have to be made up for in the wall, floor, and/or fenestration. The same idea is true in the case of the application of rigid foam. Further incentives and a demanding market would be needed to drive the manufacturer to stock new products conducive to installing rigid foam.

Issues with Building Code Compliance

- Obstacle: With new technologies, manufacturers often have concerns about their compliance with the code. Since these technologies have not been used in the past, the code might necessitate testing in some cases. This may increase the time and effort required for adoption, thus deterring manufacturers from embracing the new technology. For instance, in order to comply with the Manufactured Home Construction and Safety Standards, the expanded polystyrene foam insulation needs to meet several criteria. If the thickness of the board exceeds 1”, it needs to be tested in accordance with testing procedures described in the Illinois Institute of Technology Research Institute Report, “*Development of Mobile Home Fire Test Methods to Judge the Fire-Safe Performance of Foam Plastic Sheathing and Cavity Insulation*, IITRI Fire and Safety Research Project J-6461, 1979” or other full-scale fire tests accepted by HUD. Also, if the foam board is to be used in Wind Zones 2 or 3, each of the manufactured-home wind-resisting parts have to be designed by a professional engineer or architect to resist the design wind loads specified in ANSI/ASCE.

- Recommended action: By means of extensive research, new advanced technologies can be incorporated within the code, thus encouraging manufacturers to embrace them while also meeting the code. This would also make the code more stringent, ensuring higher standards of energy efficiency. Importantly, the initial advanced wall and roof options proposed in this research have been approved as code compliant.

Industry and Policy Barriers

Some barriers to the acceptance of energy-saving technologies relate to fitting into existing ways the industry demonstrates superior performance of their homes. For example, national energy efficiency programs, such as ENERGY STAR®, are popular with the industry and a major conduit for expressing increased value associated with improved efficiency. Being able to demonstrate that the new technologies can be folded into these programs is a key element to their success in the market. The following are several examples of industry and policy barriers associated with this work and suggested follow up actions.

Insufficient Incentives

- Obstacle: The ENERGY STAR for Manufactured Homes program was slow to take hold in the manufactured housing industry until utilities stepped in and began to offer incentives.

  Incentives were critical because manufactured housing buyers generally are low- to moderate- income households that struggle to afford the higher costs associated with ENERGY STAR features. The ability of incentive programs to generate a significant volume of sales was first demonstrated by the Tennessee Valley Authority (TVA) when they began offering cash incentives to manufacturers across the Southeast for making certified ENERGY STAR homes. The program experienced success because TVA provided generous incentives to manufacturers selling and installing ENERGY STAR certified homes sited in all of Tennessee, and contiguous stretches of Mississippi, Alabama, Virginia, and Kentucky. The program took the guesswork out of offering the energy-saving option to homebuyers; customers were offered free upgrades on the spot by retailers. They were able to make ENERGY STAR standard since the associated higher cost had been offset entirely by the incentive. ENERGY STAR became the path of least resistance.

TVA implemented incentives that covered all additional upfront costs to the upgrades and combined related incentives, removing all financial barriers to each party involved while producing vast energy savings. ENERGY STAR construction began to take hold as standard construction practice in these areas because it made more financial sense for the manufacturer to build ENERGY STAR homes than to build code-minimum homes, and they could offer top quality products.

In essence, the obstacle to any energy-saving measure with extra cost is lack of adequate up- front financial incentives to promote it, financing that recognizes the value of the efficiency investment, or other cost offsets. While low-income manufactured-home buyers may need the energy-bill savings most, they have little leeway to invest in energy-saving measures of their own accord. Specifically, if codes do not require significantly extra wall and roof insulation, they must be properly incentivized by other means in order to promote the use of rigid insulation or dense-packing. If cool-roof shingles do not match the price of standard shingles, they will be harder to sell, as long as rebate programs do not include cool-roof strategies in their offered incentives.

- Recommended action: This issue of insufficient incentives requires that multiple aspects fall into place, to create a more accepting market for energy-efficiency programs. Financial incentives must be substantial enough to cover most or all of the upgrade costs, and the incentive itself must be offered widely. This may require incentivizing specific energy-efficient technologies. One approach is to incorporate the project technologies into programs that already offer attractive incentives, like ENERGY STAR, and encourage utilities in the state to consider offering ENERGY STAR incentives.

Alternative Programs

- Obstacle: Even when seamlessly integrated into well-established programs, innovative energy- efficient technologies also meet obstacles when coexisting with similarly targeted programs.

  Because many utilities' service territories are spotty at best, the lack of pervasiveness of ENERGY STAR incentives across a region that is even as small as a county leads to reluctance in taking advantage of the program; as this occurs, manufacturers often offer their own energy- efficiency upgrade options that can be offered ubiquitously and which have many of the same (but not necessarily all) features that ENERGY STAR does (Table 25). While often simpler for the manufacturer and the customer, these programs may not all align to promote the same features of efficiency, which may not incentivize more ambitious, innovative solutions across the board. If these programs were brought together under a unifying movement, along with federal incentives programs, perhaps new, innovative technologies could become a part of standard manufacturing procedure. As it stands, however, different programs maintain different requirements; for example, while the ENERGY STAR program requires the use of a properly sized heat pump in all-electric homes, several industry programs focus more on other aspects of ENERGY STAR, like duct tightness or specific envelope upgrades. This point is graphically depicted in Table 25, which compares ENERGY STAR's basic requirements for all-electric, manufactured homes with two industry energy-efficiency upgrade programs.

As shown in Table 25, these programs have a lot of overlap, but each comprises different energy-saving measures. New, innovative technologies are not favorable methods to fulfilling these programs.

Table 25: Requirements for Manufactured Home Energy Efficiency Programs

	ENERGY STAR	Efficiency Program 1 (Manufacturer A)	Efficiency Program 2 (Manufacturer B)
Space conditioning equipment	Properly sized heat pump	n/a	Properly sized air conditioner; no heating-equipment specification
Water heater	Efficient water heater (depending on package)	Extra insulated	n/a
Envelope insulation	Insulation to achieve max allowed U_o value by region	R-33/11/22 (roof/walls/floor) (Equivalent to ENERGY STAR Region 3 insulation levels)	n/a
Windows	Maximum SHGC determined by region	Low-E, double pane	Low-E, double pane (only with additional Energy Management Package)
Extra envelope air-sealing	n/a	Yes	Yes
Ducts	Air-tight and well insulated	Well insulated	Air-tight and well insulated
Programmable thermostat	Usually, depending on package	Yes	n/a
Other	n/a	n/a	Radiant barrier roof sheathing (with additional Energy Management Package); graduated air-delivery system for balanced airflow

Source: The Levy Partnership, Inc.

- Recommended action: With incentive providing an effective mechanism for moving new technology into practices, particularly when wedded to programs that already have traction in the market, actions should be taken to fold the project technologies into ENERGY STAR and other meaningful programs. With new code requirements around the corner, there will be an opportunity to raise the efficiency bar for these programs. Coordinating these programs with manufacturer-facilitated programs will be important, especially as thermal requirements change across the industry.

Knowledge Transfer

- Obstacle: For a building technology to be accepted in industry, its value must be communicated and understood by the builder, the retailer, and the consumer. Codes and incentives programs can drive the adoption of new technologies, but moving beyond code requires demonstrating the value proposition of these technologies. Retailers must understand the benefits to the consumer, specifically how it impacts affordability and financing, while the manufacturer must be capable of effectively and efficiently employing the technology in the factory setting. The communication between manufacturer and retailer must be seamless, coordinating on how the technologies will be incorporated in the home and related impact on the home operation, if any. Currently, neither party is well equipped to take on these responsibilities e especially when the topic is new and innovative building technologies.
- Recommended action: Information about the benefits of the technologies and the best ways to implement them should be developed and communicated to the industry. One strategy that would further market acceptance would be to incorporate the technologies into the ENERGY STAR program.

Next Steps

Influence of National Policies and Incentive Programs on Energy Efficiency

While a few of the recommended actions may offer significant challenges, there are several factors that are likely to accelerate the pace of innovation and move the industry to more rapidly embrace energy-saving measures. First, the industry's thermal standards will be overhauled within two years (United States Department of Energy, 2016), following a long pause between upgrades; while the IECC code changes every three years, the HUD code thermal standards have remained virtually the same since 1994.

Once HUD thermal standards are raised and begin overlapping with the requirements of energy-efficiency programs, these programs will need to change as well. This type of lock-step change is seen elsewhere in the building industry; for example, federal requirements for appliances push up the requirements for ENERGY STAR. The changes in the standard have long been anticipated, and The Levi Partnership, along with industry partner Systems Building Research Alliance (SBRA), is actively engaged with the United States Environmental Protection Agency to revise and update the ENERGY STAR program for manufactured homes. This offers an opportunity for folding in the project results.

Promoting Energy Efficiency

There are several strategies that can be instrumental in driving the building industry towards energy efficiency. Integrating new advanced technologies into programs like ENERGY STAR will be vital to creating awareness of their value within a building design. Furthermore, having manufacturers work with federal program designers could not only lead to the development of feasible programs that can be instituted in the factory, but can also help minimize crowding of available programs, thus maximizing their effectiveness. Ensuring that these programs work together instead of separately is also crucial to their success.

Offering the right financial motivation, such as temporary incentives for owners at the start of new program implementation, could further encourage and establish the use of energy-saving technology as the norm. Additionally, direct contact with plants and retailers can help overcome any technological barriers to implementing energy-saving measures.

CHAPTER 6: Laboratory Testing and Physical Evaluation

Walls: Riverside Advanced Wall Assemblies

This task was planned to be performed in conjunction with the component prototyping event (described in Chapter 3) of the developed advanced wall designs. The advanced wall design – stud walls with continuous, exterior high R-value insulation – was component prototyped and tested for structural performance as required for compliance under the Manufactured Home Construction and Safety Standards or the HUD code. This evaluation provided a critical context for the design development work by characterizing the structural capacity and limits of the advanced wall concept.

A racking test was conducted on developed wall designs to evaluate structural compliance with ASTM E72-80 or E564 as required for compliance under the HUD standards. As stated earlier, the objective of the test was to determine the ultimate racking capacity of a framed shear wall with and without gypsum board adhered to one side and siding nailed to the opposite side.

This test evaluated the shear capacity of a typical sample section of the framed wall, supported at the base and having load applied in the plane of the wall along the edge opposite the rigid support and in a parallel direction. The test determined shear stiffness and strength of any structural light-frame wall configuration to be used as a shear-wall on a rigid support.

The advanced wall design being tested – stud walls with continuous exterior insulation – was prototyped with two exterior insulation products; Styrofoam and Foam Control Nailbrace.

Styrofoam is an XPS (extruded polystyrene) rigid insulation product manufactured by Dow Corporation, while Foam Control Nailbrace incorporates expanded polystyrene (EPS) insulation laminated onto a structural engineered wood sheathing backer and is manufactured by AFM Corporation. (For details on the advanced wall designs based on these products refer to “Wall Performance Specifications” in Chapter 3.

One of the major issues of concern was the durability of the window attachment to the structural frame when the window partially or entirely sits over the exterior insulation. Three methods of detailing the window frame were considered for comparative analysis in Riverside:

(1) having the window sit on the foam insulation and secured to the frame with nails; (2) creating a buck lumber frame around the window; and, (3) inserting a thin profile rail or clip that attaches to the frame and supports the window. The three options are shown in Figure 116 through Figure 118. Appendix C contains additional information on the wall laboratory testing.

Figure 116 shows a simple installation option where the window frame bearing rests on the foam.[6]

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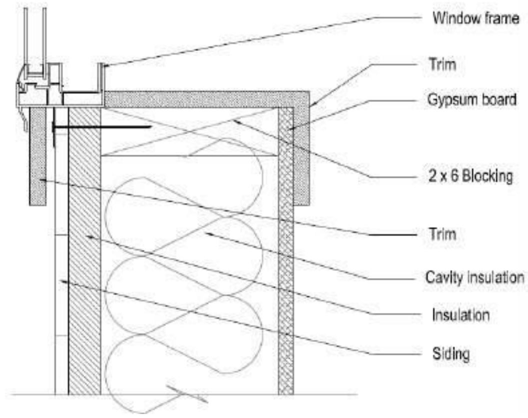
[6] Placing the flange over the siding is standard industry practice.

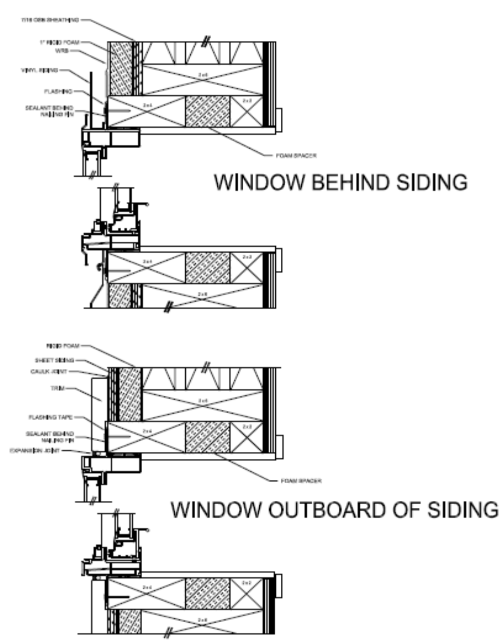
Figure 116: Detail 1 – Window Frame Bearing on Foam



Source: The Levy Partnership, Inc.

Figure 117 is a wall opening detail with a protruding frame designed to provide the window with solid wood bearing. This design also includes a foam spacer that reduces thermal bridging.

Figure 117: Detail 2 – Window Framing with Buck Lumber



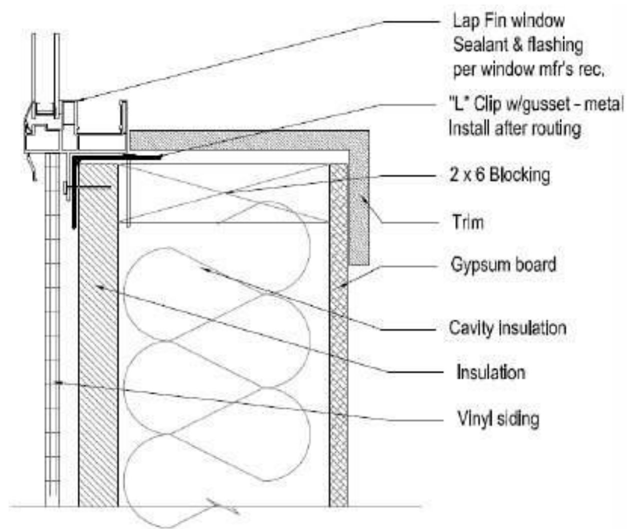
Source: The Levy Partnership, Inc.

Figure 118 shows detail of a window frame installation option with a metal L-section providing a rigid surface to support the window.

Results

Racking tests were planned on the Dow and AFM products in a few different configurations. The purpose of the racking tests was to develop a ballpark estimate of racking strength, a preliminary figure to guide future analysis and design direction. A single test was to be performed for each wall following the ASTM E564 protocol with regard to load application and load cycling (typically the testing protocol involves the averaging of results from three samples).

Figure 118: Detail 3 – Window Framing with Metal L-Section



Source: The Levy Partnership, Inc.

Only walls with R-5 were tested, the most likely insulation level to be used in the short term. For the testing of the wall with Dow Styrofoam, the team speculated that the siding and gypsum board might impact the ultimate shear load. Four tests were conducted, two with each siding material representative of the typical products used by the factory building industry that were expected to provide some racking strength (vinyl was not tested). The siding materials were each tested with and without interior gypsum board.[7] Table 26 lists the variations of wall type combinations with Styrofoam that were subject to the ASTM E72-80/E564 racking test.[8]

[7] Testing was done on wall assemblies without gypsum board to compare results with assemblies that included gypsum board. As noted earlier, gypsum board with the proper adhesive may provide sufficient shear resistance but only in certain areas. Additional shear resistance may be needed in higher wind zones.

[8] The tests followed the procedures described in the ASTM protocol except only a single sample of each wall was tested. The full qualifying protocol requires testing three samples of each wall and averaging the results.

Table 26: Racking Test Results – Stud Walls with Styrofoam

Case No.	R-Value (thickness)	Siding	Gypsum board present	Ultimate load	
				lb	plf*
RD1 (a)	R-5 (1 in.)	LP SmartSide	Yes	6,701	335
RD1 (b)	R-5 (1 in.)	LP SmartSide	No	5,842	292
RD2 (a)	R-5 (1 in.)	Cempanel	Yes	4,523	226
RD2 (b)	R-5 (1 in.)	Cempanel	No	6,200	310

*** Assumes a 2.5 safety factor.**

Source: The Levy Partnership, Inc.

Two walls using AFM Nailbrace were tested for racking strength with and without interior gypsum board. It should be noted that Nailbrace was not fastened at the top and bottom plates for these tests.[9] AFM noted that attaching Nailbrace with screws will substantially improve the load capacity of the wall. The results are shown in Table 27 below.

Table 27: Racking Test Results – Stud Walls with Foam-Control Nailbrace

Case No.	R-value (thickness)	Siding	Gypsum board present	Ultimate load	
				lb	plf*
RA1 (a)	R-5 (1⅝ in.)	LP SmartSide	Yes	7,154	357
RA1 (b)	R-5 (1⅝ in.)	LP SmartSide	No	Excessive deflection	na

*** Assumes a 2.5 safety factor.**

Source: The Levy Partnership, Inc.

Four walls using Dow Styrofoam were tested for racking strength distinguished by the type of siding applied and the use of interior gypsum board. The results are shown in Table 28.

Table 28: Racking Test Results – Stud Walls with Styrofoam

Case No.	R-Value (thickness)	Siding	Gypsum board present	Ultimate load	
				lb	plf*
RD1 (a)	R-5 (1 in.)	LP SmartSide	Yes	6,701	335
RD1 (b)	R-5 (1 in.)	LP SmartSide	No	5,842	292
RD2 (a)	R-5 (1 in.)	Cempanel	Yes	4,523	226
RD2 (b)	R-5 (1 in.)	Cempanel	No	6,200	310

*** Assumes a 2.5 safety factor.**

Source: The Levy Partnership, Inc.

[9] Absence of let-in bracing at the top and bottom was discussed after the tests but not pursued since this option was dropped from further consideration

Results and examination of the panels after testing suggest the following:

All panels achieved the target 210 plf, including two walls built without interior gypsum .The siding (LP SmartSide and Cempanel) likely contributed some shear value (Figure 119).

Figure 119: Wall Panels

Source: The Levy Partnership, Inc.

The ultimate load for RD2(a) was lower than RD2(b), despite the addition of gypsum board. This is a counterintuitive result and suggests the preliminary nature of these tests. The low strength of RD2(a) is an outlier and suggests that this test should be revisited.

Figure 120: RD2 Test

Source: The Levy Partnership, Inc.

The RD1 tests indicated that the addition of gypsum adds to the shear strength, as expected.

Figure 121: Gypsum Adds to Shear Strength

Source: The Levy Partnership, Inc.

Examination of the test samples indicated that the fasteners in the foam bent in two dimensions – a result of cantilevering the nails.

Figure 122: Nail Cantilevering

Source: The Levy Partnership, Inc.

The AFM Nailbrace panel is a single application structural capacity, CI, a nailing surface for the siding material and an air barrier. The combination promised to eliminate steps in the manufacturing process. The mockup and shear testing involved one foam type and thickness, although it should be noted that Nailbrace can be manufactured in varying thicknesses with different OEM produced insulation materials.

Analysis

Two walls using AFM Nailbrace were tested for racking strength one with and the other without interior gypsum board. It should be noted that Nailbrace was not fastened at the top and bottom plates for these tests.[10] AFM noted that attaching Nailbrace with screws will substantially improve the load capacity of the wall. The results are shown in Table 29 below.

Table 29: Racking Test Results – Stud Walls with Foam-Control Nailbrace

Case No.	R-value (thickness)	Siding	Gypsum board present	Ultimate load	
				lb	plf*
RA1 (a)	R-5 (1⅝ in.)	LP SmartSide	Yes	7,154	357
RA1 (b)	R-5 (1⅝ in.)	LP SmartSide	No	Excessive deflection	na

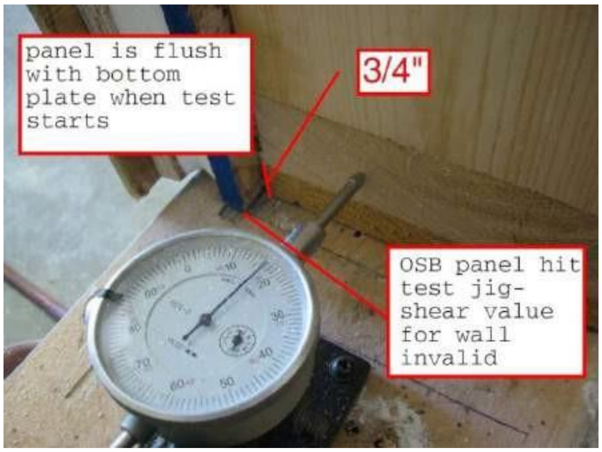
*** Pounds per linear foot. Assumes a 2.5 safety factor.**

Source: The Levy Partnership, Inc.

Results and examination of the panels after testing suggest the following:

The wall with the gypsum board attained a significant ultimate load with used in combination with the Nailbrace. The lack of nailing at the top and bottom plate is likely to have significantly reduced the racking strength of the wall.

Figure 123: Wall Test



Source: The Levy Partnership, Inc.

[10] Absence of let-in bracing at the top and bottom was discussed after the tests but not pursued since this option was dropped from further consideration.

During testing, the RA1(b) wall deformed, coming in contact with the testing device (see photo above) prior to failure due to bending of the fasteners. This negated the result and created a challenge to applying the racking apparatus.

Figure 124: Wall Deformation

Source: The Levy Partnership, Inc.

Fleetwood expressed interest in running an additional shear test on Nailbrace using screws instead of nails. Tests should be run with screws all around the perimeter, including top and bottom plates.

Figure 125: Racked Foam Panels

Source: The Levy Partnership, Inc.

Inferences and Recommendations

The research described in this section was part of a multiphase program with the goal of identifying and moving toward commercial acceptance of envelope construction methods that are far more efficient than current practice and specifically geared to meet the needs of factory builders. This effort was focused on wall component development and the initial testing of some of the solutions developed.

Among the observations and inferences of the design-development and testing phase are the following:

- The stud walls with Styrofoam assemblies achieved the target 210 pounds per linear foor (plf), including two walls built without interior gypsum. This product offers structural stability to the wall design and meets the HUD requirements for Wind zone 1 which covers most of the United States.
- The stud walls with AFM Foam-Control Nailbrace assemblies with the gypsum board attained a significant ultimate load that was higher than the threshold limit required for HUD Wind zone 1. Manufacturers claim higher numbers with the top and bottom ends fastened to the framing amd also recommend further research with using screws instead of nails.

Among the key findings from the limited testing and mockups of the wall designs proposed by Dow and AFM are the following general points:

- The general sense of the technical review group was that Dow's Styrofoam has real potential and the hurdles to its use and additional effort that would be required to reach proof-of- concept is manageable – Styrofoam is a promising product for factory builders. However, questions about cost, compliance with HUD standards, and production friendliness need to be addressed.
- AFM's Nailbrace has much to recommend it, including its ability to be an almost-all-in-one wall solution. However, the preliminary reaction of the industry and supplier group assembled for the test is that the product has significant drawbacks (for example, need to use screws instead of nails, lack of flexibility with regard to furring location, weight of the panel) that represent formidable hurdles weighing against this option.

Roofs: Phase 1 – Jamestown Advanced Roof Assemblies

This section focuses on the laboratory testing and physical evaluation of the four advanced roof designs developed in conjunction with this specific task (see Component Prototyping section in Chapter 4 for details of the developed roof designs). Prototype samples of the four solutions were evaluated for issues associated with system assembly and tested for improved thermal performance, propensity to moisture issues and structural stability.

Test Approach

Samples of four advanced roof designs (compared to a base case) and the selected advanced wall design were subject to testing and long term monitoring over typical heating and cooling seasons. These envelope assemblies were evaluated for issues associated with system assembly and tested for improved thermal performance, propensity to moisture issues and structural stability. Multiple advanced roof assemblies were built in a single test structure to provide a side-by-side assessment of thermal and moisture performance and ease of manufacture. Long and short-term testing was conducted in hot and cold climates. Instrumentation was installed on the unit for long-term monitoring to measure thermal and moisture performance with remote data collection.

Short term heating-season testing was conducted in the last week of November 2014 and the unit was set-up with sensors for long-term monitoring and data collection. In the spring of 2015, the thermostat settings in the test unit were changed for the summer-time testing. Similar to the heating season monitoring protocol, the unit was set-up for a period of 4 to 5 months for cooling season monitoring and assessment.

A detailed description of the design and construction of the base case and the advanced roof design assemblies is provided below:

- Base design: Conventional roof construction with standard density blown insulation in the attic with baffles providing ventilation path.
- Design 1 - Vented attic roof with dense-packed insulation at eaves: Dense-packed/compressed blown insulation to increase the thermal performance at the eaves and standard density loose fill insulation at the center of the attic.
- Design 2 - Vented attic roof with compressed batts at eaves: Combines two types of insulation to achieve a more uniform U-value across the attic; blown/loose-fill insulation at the center with compressed, unfaced batt insulation at the eaves.
- Design 3 - Vented, sealed attic roof with dense-packed blown insulation at the eaves: Vented, sealed attic roof with dense-packed insulation at the eaves and standard density blown insulation in the field. An air barrier with high perm rating is used to seal the attic against any air movement/communication with the vented upper roof. This roof design, in particular, is being evaluated for impact on thermal performance due to the restriction on air movement by the air barrier.
- Design 4 - Unvented, sealed attic roof with dense-packed blown insulation at the eaves: This roof option incorporates an unvented, sealed attic with dense-packed blown insulation at the eaves and standard density blown insulation in the field area. A diffusion vent (a vapor permeable air barrier vent) is used at the ridge that would allow the accumulated moisture to dry out via vapor diffusion while still acting as an effective air barrier that reduces heat loss.

The testing apparatus was a single section manufactured home structure measuring approx. 14 feet wide and 34 feet long. A full scale roof was built and placed over 7 foot high side and end walls, with no interior partitions. The roof was divided into seven bays with five central bays each about 6 feet in width. The end bays, about 2 feet wide, act as buffer zones ensuring similar thermal boundaries between the experimental design bays. Attic insulation levels between the design bays were similar. The end buffer bays had insulation similar to the Base case.

The designs are representative sections of the four advanced roof designs and the baseline case. Each design extends from eave-to-eave and each bay is isolated (from a moisture and thermal flow standpoint) from adjacent bays by means of an insulated partition wall and air sealing measures (such as tape, foam and gaskets). A longitudinal section of the experimental roof is shown in Figure 62 in Chapter 4, and the assemblies are described in detail in Figure 63 to Figure 72.

The interior of the house was an open layout with no interior partition walls. There were two doors on the opposite sidewalls of the unit. No windows were installed. Walls and floors were built and insulated as per specifications. Specifications and details of the manufactured housing unit planned for the prototyping and testing are listed in Chapter 4, Table 13. The roof was subject to long-term monitoring and assessment for hot and cold climates with sensors installed to monitor temperature, pressure and humidity levels within the roof cavities, at possible condensation surfaces and in ventilation pathways. Interior humidity conditions were artificially introduced and the temperature inside controlled. Temperature and relative humidity set points were controlled remotely via a data logger. At the conclusion of the experiments the assemblies were disassembled and checked for any evidence of condensation, moisture accumulation or moisture-related damage.

Results

Weather Data and Interior Conditioning

The on-site weather station measured 2,749 heating degree days (HDD65) for the heating season monitoring period (11/21/2014 to 4/7/2015), and 869 cooling degree days for the cooling period (5/1/2015 to 8/10/2015). Typical meteorological year data is not available for the Jamestown- Sonora area; two of the nearest weather stations' typical full heating season HDDs range from 2,300 (Modesto) to 7,700 (South Lake Tahoe), while typical cooling season CDDs range from 1,200 (Modesto) to less than 50 (South Lake Tahoe). Average onsite wind speed and insolation over the heating analysis period was 1.4 mph and 12.8 W/ft^2, respectively, and 2.0 mph and 28.1 W/ft^2 over the cooling analysis period; precipitation was not recorded. Exterior relative humidity typically showed wide diurnal swings of ~40 percent to 95 percent in the heating season and was less pronounced in the summer.

The temperature and relative humidity of the interior space of the test house were maintained between 70-74˚F and 50-57 percent RH. The 2˚F offset between heating and cooling equipment set points was maintained to prevent the appliances from running simultaneously.

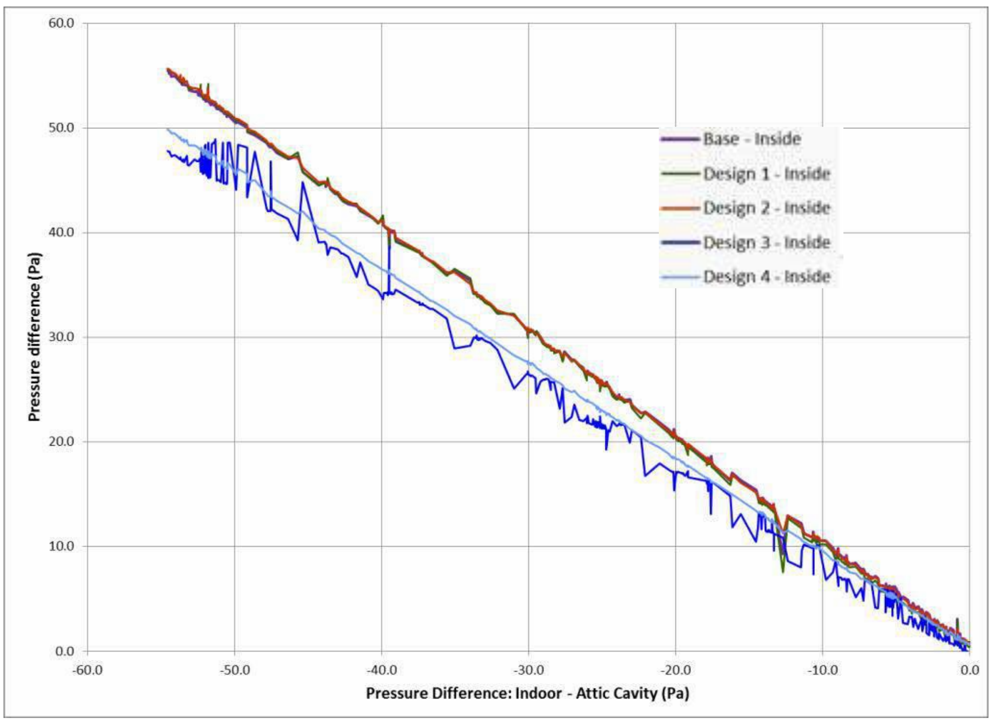
Attic Cavity Depressurization Test

On November 21, 2015, the test unit indoor space was de-pressurized relative to outdoor ambient conditions to gauge the relative levels of air leakage to the outside of the test roof designs. The total leakage area across the ceiling from each attic bay to the indoor space was equal by design. Operating a duct blaster fan at various speeds while the data-logging equipment recorded pressure differentials between the indoor space and outdoor ambient and between the test roof cavities and the indoor space yielded the performance curve shown in Figure 126. The curve shows the degree to which attic cavity pressure is dependent on outdoor ambient pressure; because the base case and test Designs 1 and 2 were vented to outdoor ambient, the pressure difference was greater for these designs than the pressure differences for Designs 3 and 4, as expected.

Heating Season Thermal Performance

The negative numbers in Table 30 reflect the average direction of heat flow in winter conditions – from the interior living space to the attic. Figure 127 shows typical heating season values recorded by the heat flux sensors, with the conventional attic eave exhibiting the highest rate of nighttime heat loss. The eave sensors in the dense-packed blown insulation and compressed fiberglass batt conditions recorded average heat transfer rates that were 30 percent and 40 percent less, respectively, than that of the base case eave sensors with only loose blown insulation. In the base case conditions of a vented, unsealed attic with loose blown insulation in both the eaves and the center of the attic, the ceiling-center average heat transfer rate measured approximately 50 percent that of the corresponding eave heat transfer rate. The average ceiling-center heat flux transfer rates for the vented, sealed attic and the unvented, sealed attic designs were 9 percent and 16 percent less, respectively, than the average for the typical vented attic. A limitation of the spot measurements of heat transfer conducted here is that the heat transfer may not be totally uniform throughout the eave or ceiling center, because of heterogeneity in insulation density and air sealing (for example, compressed fiberglass batt insulation might not fully fill the corners formed between the rafters, sheathing, blocking and ceiling gypsum board).

Figure 126: Depressurization Performance Curves for the Test Roof Cavities



Source: The Levy Partnership, Inc.

Graphically, heat flux appears to correlate more closely with roof deck temperature than outdoor air temperature. This is most likely because the roof deck temperature incorporates solar gain as well. As expected, heat loss through the dense-packed blown insulation and compressed-batt eave designs was lower than at eaves with standard density blown insulation.

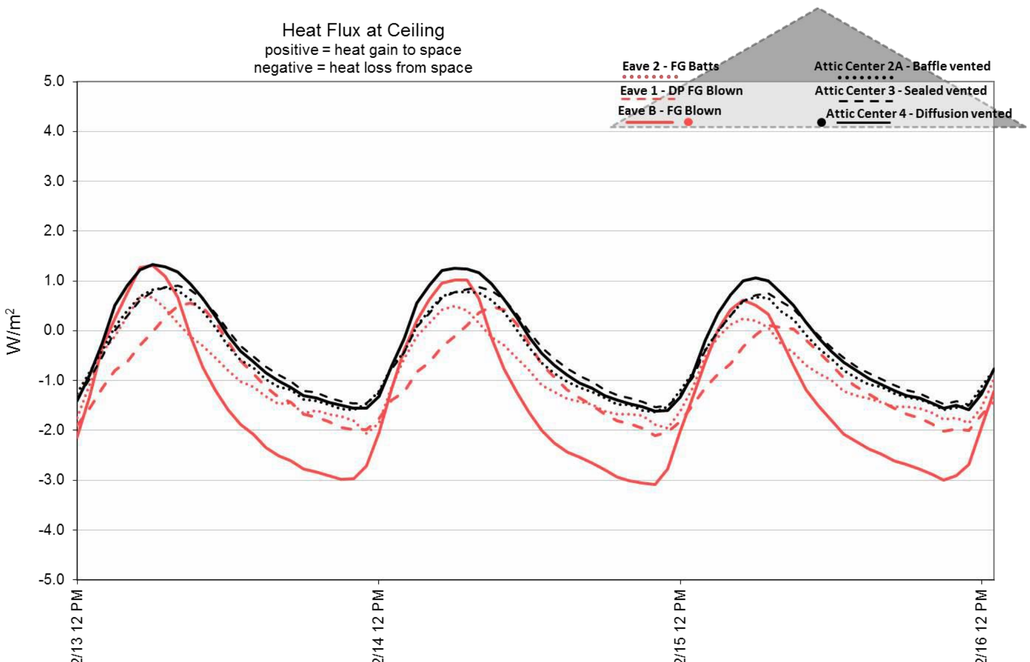
On days when the outside temperature dropped below average, heat loss through the eave with compressed batts was marginally lower than the dense-packed eave designs. At the attic-center condition, losses were smallest through the unvented, sealed attic than any of the other designs.

Table 30: Heating Season Heat Flux Sensor Measurements

	Eaves			Center-attic		
Heat Flux per Attic Design Type	**Vented attic w/ standard blown eave insulation (base attic)**	**Vented attic w/ dense-packed blown eave insulation**	**Vented attic w/ compressed batt eave insulation**	**Vented, unsealed attic (base attic)**	**Vented, sealed attic**	**Unvented, sealed attic**
Average W/m^2	-1.89	-1.33	-1.14	-0.91	-0.83	-0.76
Total Wh/m^2	-6,096	-4,302	-3,670	-2,955	-2,668	-2,440

Source: The Levy Partnership, Inc.

Figure 127: Typical Daily Range of Heat Transfer Values at Heat Flux Sensors in Winter



Source: The Levy Partnership, Inc.

Cooling Season Thermal Performance

Cooling season performance did not directly follow that of the heating season. The positive numbers in

Table 31 reflect that on average, the indoor space gained heat from the attic bays and the better-performing designs in the heating season tended to be the worst in the cooling season.

Table 31: Cooling Season Heat Flux Sensor Measurements

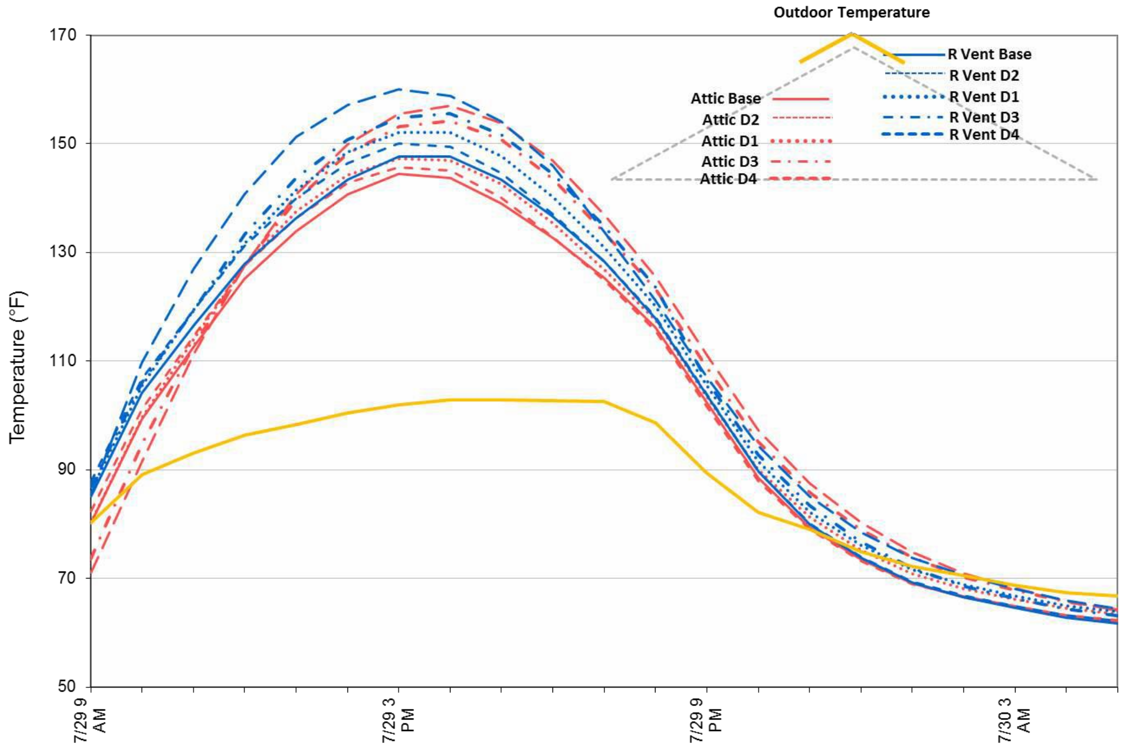
	Eaves			Attic Center		
Heat Flux per Attic Design Type	Vented Attic w/ Standard Blown Eave Insulation (Base Attic)	Vented Attic w/ Dense- Packed Blown Eave Insulation	Vented Attic w/ Compressed Batt Eave Insulation	Vented, Unsealed Attic (Base attic)	Vented, Sealed Attic	Unvented, Sealed Attic
Average W/m2	0.60	0.63	1.07	0.86	1.09	1.17
Cooling season Net Wh/m2	1,448	1,502	2,561	2,075	2,627	2,818
Maximum W/m2	6.1	4.8	9.0	4.2	4.4	4.7
Minimum W/m2	-3.3	-2.2	-2.4	-1.7	-1.6	-1.6
Total Gains to Interior Space Wh/m2	2,911	2,243	3,386	2,498	2,931	3,202
Total Losses from Interior Space Wh/m2	-1,463	-742	-825	-424	-304	-384
Standard Deviation	2.1	1.5	2.2	1.3	1.4	1.6

Source: The Levy Partnership, Inc.

Further, the peak heat flux rates do not correlate with the average rates; it is suspected that the test conditions where airflow was reduced caused those bays to retain heat from both the outdoor ambient air and solar irradiance on the roof deck, raising the average temperature. In addition to the ceiling center in both sealed attics, the eave in the vented attic with compressed batt insulation exhibited a high average rate of heat flux; this may indicate that the compressed batts were pressing the under-deck baffles and restricting ventilation airflow there. The base condition loose-blown insulation eave and vented, unsealed attic were correlated with the least amount of heat gain to the interior living space.

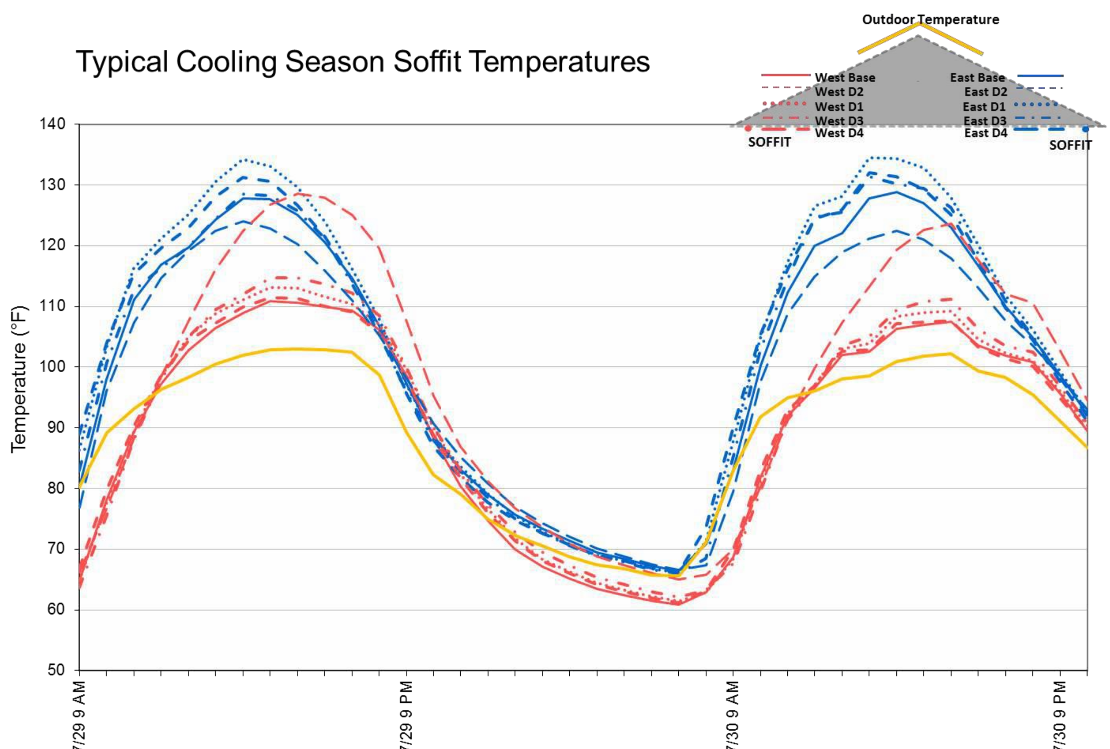
Figure 128 shows the highest temperatures recorded in the attic cavities on July 29, 2015. Trend lines in blue and red show temperatures at the ridge vent and center of attic cavity, respectively, for each design. The sealed, unvented attic (Design 4) shows the highest temperatures, followed by the unsealed, vented attic (Design 3), and then the three vented, unsealed attic designs. The soffit temperatures in Figure 129 show higher temperatures on the east side of each attic design compared to the west soffits; while both sides of the test building were un-shadowed throughout the day and received full sunlight, the east side of the building was within 10 meters of trees and other structures at greater elevation and the west side was exposed to the hillside, perhaps cooled slightly by prevailing winds. The peak temperature of the west soffit of Design 2 is conspicuously higher than the other designs and might be related to constriction of the baffles beneath the roof sheathing by the compressed fiberglass batts.

Figure 128: Attic and Roof Ridge Temperatures on Hot Summer Day



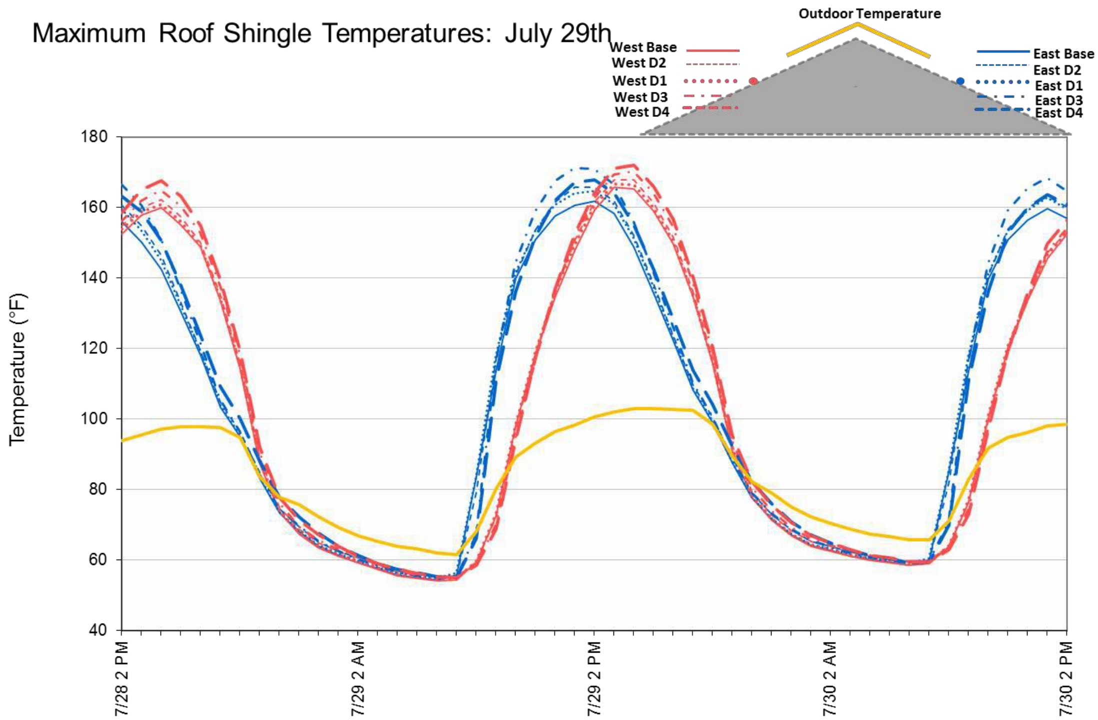
Source: The Levy Partnership, Inc.

Figure 129: Soffit Temperatures on July 29, 2015



Source: The Levy Partnership, Inc.

Figure 130: Peak Roof Shingle Temperatures, July 29, 2015



Source: The Levy Partnership, Inc.

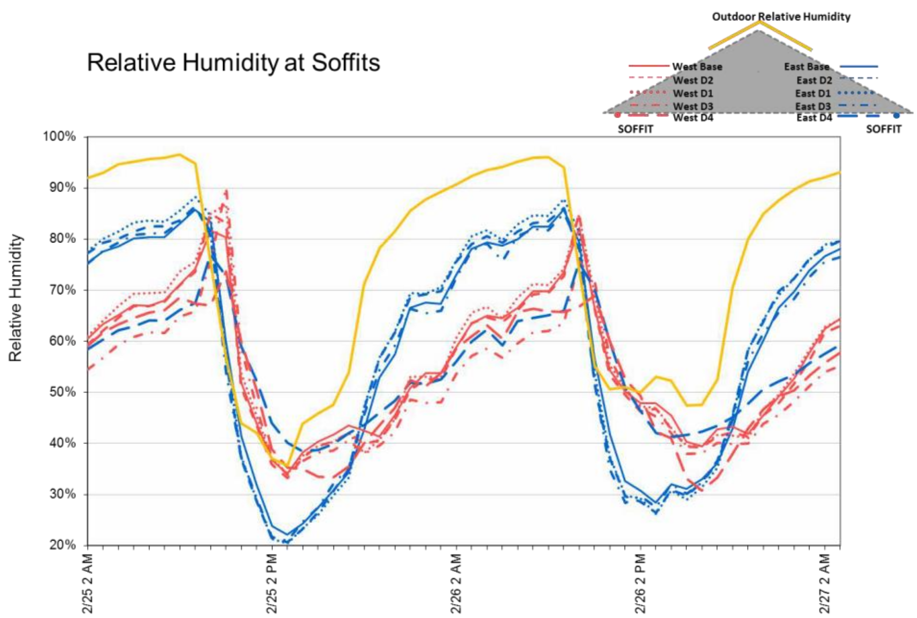
The roof shingle temperatures across the five designs shown in Figure 130 are not markedly different; however, there is as much as a 5˚C difference between the designs which seems to again correlate the unsealed, vented attic designs with the lowest temperatures.

Moisture Performance

The moisture content of the sheathing remained within reasonable limits (15 percent or lower) for all the roof designs. The standard range for mold occurrence and its continued growth is 19 percent or greater (Forest Products Laboratory, 2015). However, peak heating season moisture levels were ~2 percent higher in Design 4 when compared to the other four. This may have implications for other climates. Interestingly, sheathing moisture content for each design dropped to ≤7 percent (the sensors' lower functional boundary) over the cooling season, except Design 1 – which featured an unsealed, vented attic space and dense-packed blown insulation.

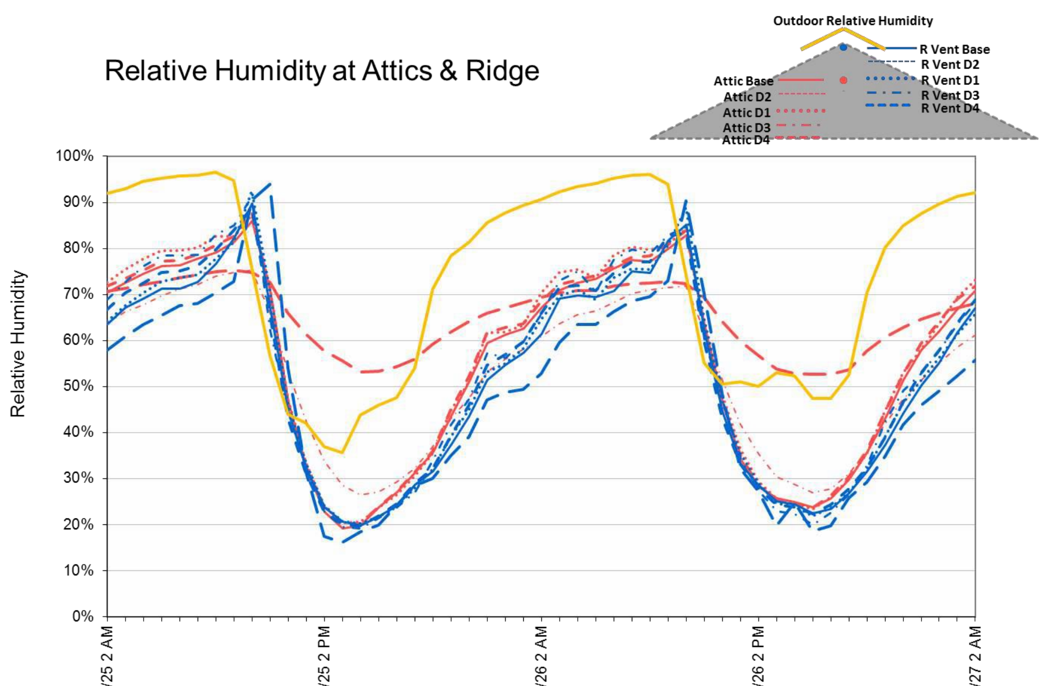
Relative humidity during the height of the heating season was fairly homogenous throughout the designs in their soffits (Figure 131), attic cavities and roof ridges (Figure 132) - with the exception of Design 4, where soffit RH exhibited a similar average value but with a smaller deadband and where attic cavity RH was slightly above average, again with a reduced deadband. Further, the attic cavity relative humidity in Design 4 remained at or above 70 percent for an entire week in early January (see Figure 133), which, in conjunction with high surface moisture content in the roof sheathing and framing, could result in microbial growth (Forest Products Laboratory, 2015); however, the peak moisture content in the sheathing in this design did not exceed 16 percent at any point in the heating or cooling seasons monitored. It is worth noting that the moisture measurements were made within a year of construction. Wood moisture content may further decline as the wood ages.

Figure 131: Typical Soffit Relative Humidity in Heating Season



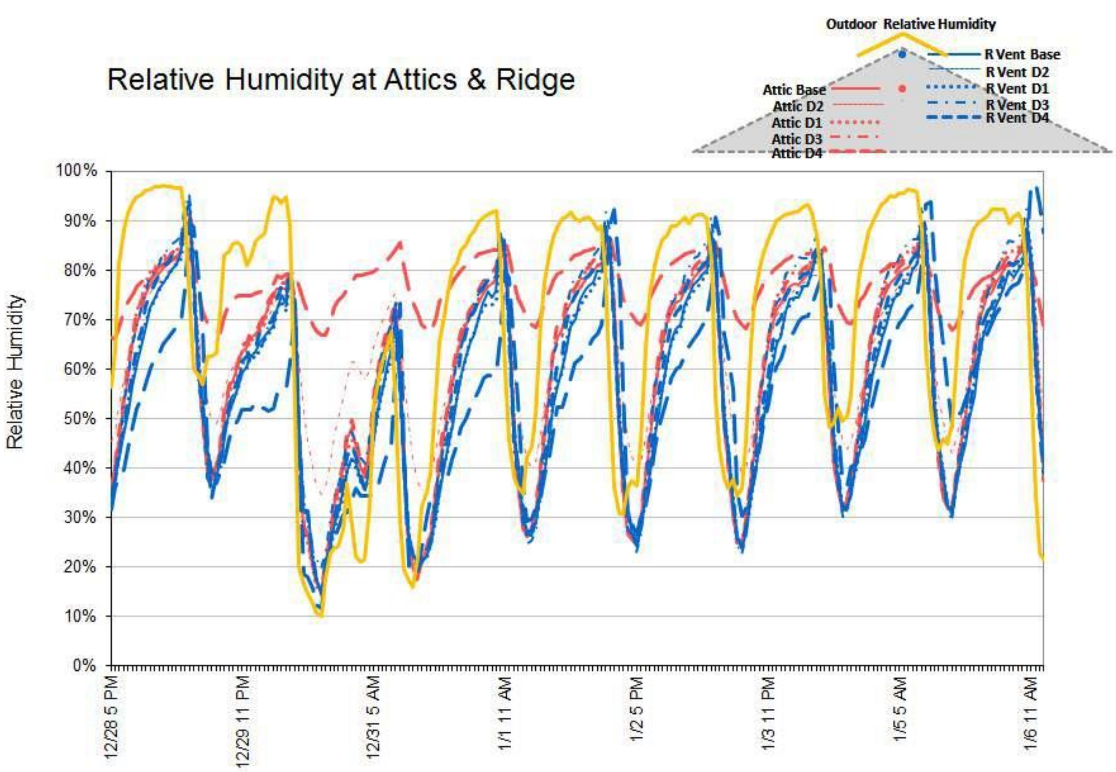
Source: The Levy Partnership, Inc.

Figure 132: Typical Attic and Roof Ridge Relative Humidity in Heating Season



Source: The Levy Partnership, Inc.

Figure 133: Relative Humidity at 70 percent or Higher in Design 4 (unvented, sealed attic) for a Week in Mid-winter



Source: The Levy Partnership, Inc.

Analysis

Energy Savings and Utility Bill Savings

To estimate the energy savings from each roof assembly, heat flux was measured at each unique assembly. Measurements were made at the eaves with standard-density blown fiberglass, dense-packed blown fiberglass, and compressed batt, as well as at the center in the vented and unsealed assembly, the vented and sealed assembly, and the unvented and sealed assembly. Each design's total heat flux was estimated as a weighted average of the eave and center constructions as shown in Table 32. Polynomial regressions were used to create equations for heat flux as a function of ambient dry-bulb temperature and solar radiation, and total heat flux was normalized for TMY3 weather data for Stockton, California in the case of Jamestown, as this was the most proximal TMY3 data available. The same equations for each assembly were used to extrapolate energy savings in Truckee, California – a colder climate.

Table 32: Design Components for Applying Heat Flux Equations

	Eave			Center (all loose-fill)		
	Standard density	Dense-packed	Compressed batt	Vented, unsealed	Vented, sealed	Unvented, sealed
Base Case	X			X		
Design 1		X		X		
Design 2			X	X		
Design 3		X			X	
Design 4		X				X

Source: The Levy Partnership, Inc.

To estimate energy and energy-bill savings, the cooling season was assumed to be between May and October, while the heating season was assumed to be between October and May, with both May and October overlapping as potential periods of both heating and cooling. Dimensions for a standard double-wide home of 56 feet long by 27.3 feet wide were used. Efficiencies were assumed to be 14 SEER and 0.80 AFUE (Federal standards), with 5 percent duct losses. $0.16/kWh was used for electricity, and $0.79/therm was used for natural gas utility rates. Table 33 shows a sample of the analysis performed for each design. A summary of the savings for each design in each of the two climates is shown in Table 33 and Table 34.

Table 33: Estimated Annual Energy Savings in Jamestown for Design 2 versus the Base Case

		Eave	Center	Total
Area	sqft	453.48	1077.00	1530.48
Total heat flux	BTU	-26093	-39084	-65176
	kBtu heating (if gas)	971	1658	2630
Energy Use	kWh heating (if electric)	225	384	608
	kWh (cooling)	53	91	143
Utility rate	$/kBtu	$ 0.0079	$ 0.0079	$ 0.0079
	$/kWh	$ 0.18	$ 0.18	$ 0.18
Energy loss/gain	Gas-heated	$ 17.15	$ 29.35	$ 46.50
	Electric-heated	$ 49.87	$ 85.21	$ 135.09
Savings, compared to base case	Gas-heated			$ 4.41
	Electric-heated			$ 28.88

Source: The Levy Partnership, Inc.

Table 34: Estimated Annual Energy Savings in Jamestown and Truckee for All Assemblies

Total Annual Energy Savings Compared to Base Case					
	Heating fuel	**Design 1**	**Design 2**	**Design 3**	**Design 4**
Jamestown	Gas	$8.40	$4.41	$8.83	$6.53
	Electric	$31.86	$28.88	$40.29	$41.14
Truckee	Gas	$9.96	$14.05	$10.70	$9.70
	Electric	$50.06	$78.63	$55.71	$55.44

Source: The Levy Partnership, Inc.

The energy-savings calculations show that financial savings for each of these assemblies is modest if heated with natural gas, as heat-loss through the roof does not play as large a role as it would in colder climates. However, decreasing U-value through dense-packing or compressed batt may be important techniques to use in order to meet the new energy code, especially in homes with vaulted ceilings. The improvements in the eave insulation proved to be proportionately very effective, as seen in the savings derived by Designs 1 and 2. These designs' field insulation techniques were the same as those in the base case, but their eave insulation consisted of dense-packed fiberglass and compressed batt, respectively, meaning that energy savings were entirely attributable to the eaves. Minimal savings (roughly an additional $5 to $8 annually) are gained for sealing the attic and for eliminating attic ventilation.

Inferences and Recommendations

Answers to research questions:

- What is the potential for moisture related deterioration of roof materials and microbial growth associated with elevated temperature and relative humidity of the proposed new roof designs compared to typical manufactured home roof designs?

  All of the test attic designs performed well in this regard and the results do not indicate that moisture and mold growth would be an issue in this specific climate. The unvented, sealed attic (Design 4) did sustain higher average relative humidity and moisture content in the heating season than the other designs, but the recorded values fell short of critical thresholds for mold growth.

- What impact does roof ventilation have on the thermal and moisture performance of alternative roof systems?

  Decreasing levels of ventilation – from the vented, unsealed attic designs, to the vented and sealed attic, and finally the unvented, sealed attic – appeared to increase heat retention in both the heating and cooling season monitoring periods in this experiment, as was expected. Thus, the ventilation strategies that exhibited the best thermal performance in the heating season were the worst thermal performers in the cooling season. In terms of moisture performance, only the attic bay that was both unvented and sealed (Design 4) exhibited substantially higher average relative humidity, while at the same time having slightly lower peak humidity than the other designs and a mild increase in heating season sheathing moisture content. The vented attic cavity in Design 3, although sealed with a membrane, still performed comparably to the unsealed, vented attic bays in terms of relative humidity and moisture content. Interestingly, the roof sheathing in Design 1 (unsealed, vented cavity with dense-packed insulation at the eaves) showed 7.5-8 percent moisture content during the summer cooling season, slightly higher than all the other designs.

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- Which of the four alternative roof designs demonstrates superior performance in terms of thermal performance and propensity to moisture issues?

  Moisture management over the monitoring period appears acceptable for all four designs. Design 1 and the base design both showed the lowest net heat gain to the indoor living space in the cooling season; however, heat flux swings in both directions were lower in Design 1 than the base case, indicating more consistent performance. The heating season thermal performance of all four test designs was superior to that of the base design. While the attic membrane sealing and unvented strategies retained the most heat in the heating season (Designs 3 and 4), the total reduction in seasonal energy loss might not justify the added material cost and complexity of constructing these designs, leaving Design 1 as the best overall alternative to the conventional manufactured home roof in this climate.

  Cooling and heating climates may dictate different methods for roof construction. In a cool climate, dense-packing at roof eaves would be the most effective thermal measure, with the option to seal the attic for extra heat retention. In a warmer California climate, it would be best to ensure proper roof venting, while heat gain/loss at the roof eaves may be less critical. Testing could be performed in warm climates to determine the effects of increased eave and field insulation. Further research could also be done on dense-packing throughout the roof in cathedral and/or cove ceilings to demonstrate further savings of these strategies and their ability to help meet new energy codes.

Roofs: Phase 2 – Riverside Cool Roof Assemblies

As a step towards improving the thermal performance of manufactured home envelope components, tests were conducted of two strategies expected to improve the energy efficiency of the roof system: attic radiant barriers and cool roofs. Prototype assemblies comparing conventional roof construction with roofs equipped with radiant barriers and cool roofs were instrumented and monitored over the summer of 2015.

Testing and evaluation was conducted on multiple roof compartments to provide a side-by-side assessment of the thermal performance of the roof measures, including standard practice without either measure. Cooling season tests were conducted in a hot Californian climate (California Climate Zone 10) to evaluate impact on cooling loads. Sensors were installed to measure thermal performance with remote data collection.

Appendix E contains additional information on the roof laboratory testing.

Test Approach

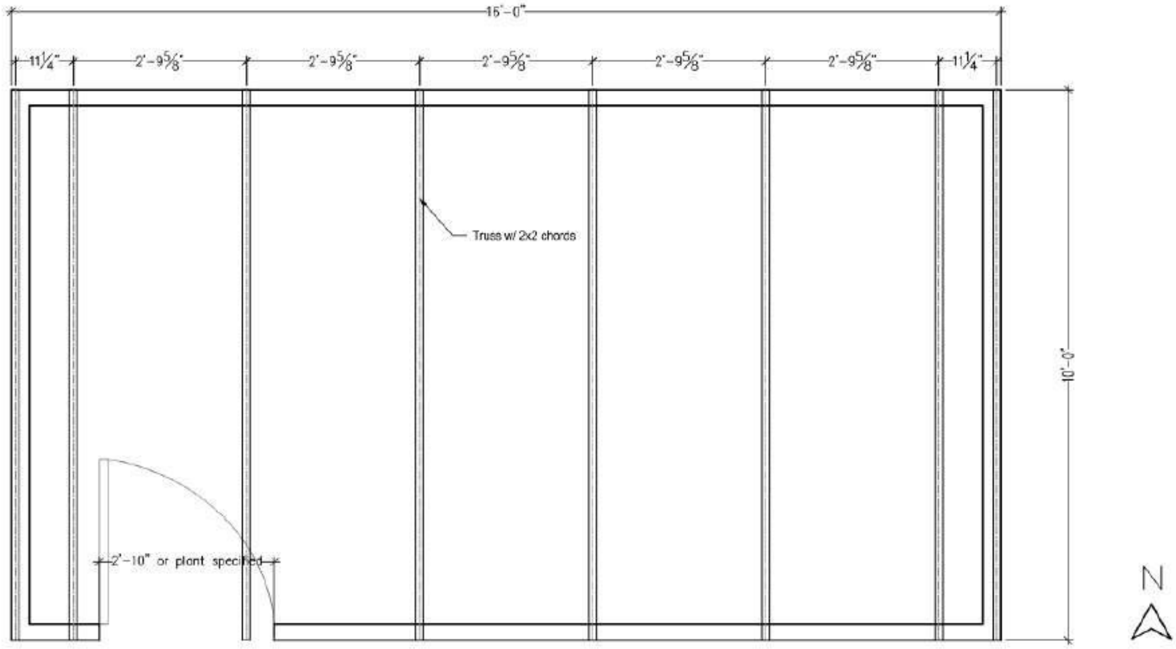
Five roof configurations were tested as follows:

- Base case: Standard roof construction with asphalt roof shingles (solar reflectance: ~0.07)
- Radiant barrier: Radiant barrier (reflectivity: ~97 percent) on the underside of the sheathing with standard asphalt roof shingles (solar reflectance: ~ 0.07)
- Cool roof (option 1): standard construction with cool-colored shingles (solar reflectance: 0.23 to 0.34)
- Cool roof (option 2): standard construction with field applied cool coating. (solar reflectance: 0.4 to 0.7)
- Combined measures: Roof with attic radiant barrier (reflectivity: ~97 percent) with cool-colored shingles (solar reflectance: 0.23 to 0.34)

The test structure was built in the Fleetwood Homes manufacturing plant at Riverside, California, and placed on the plant premises for testing.

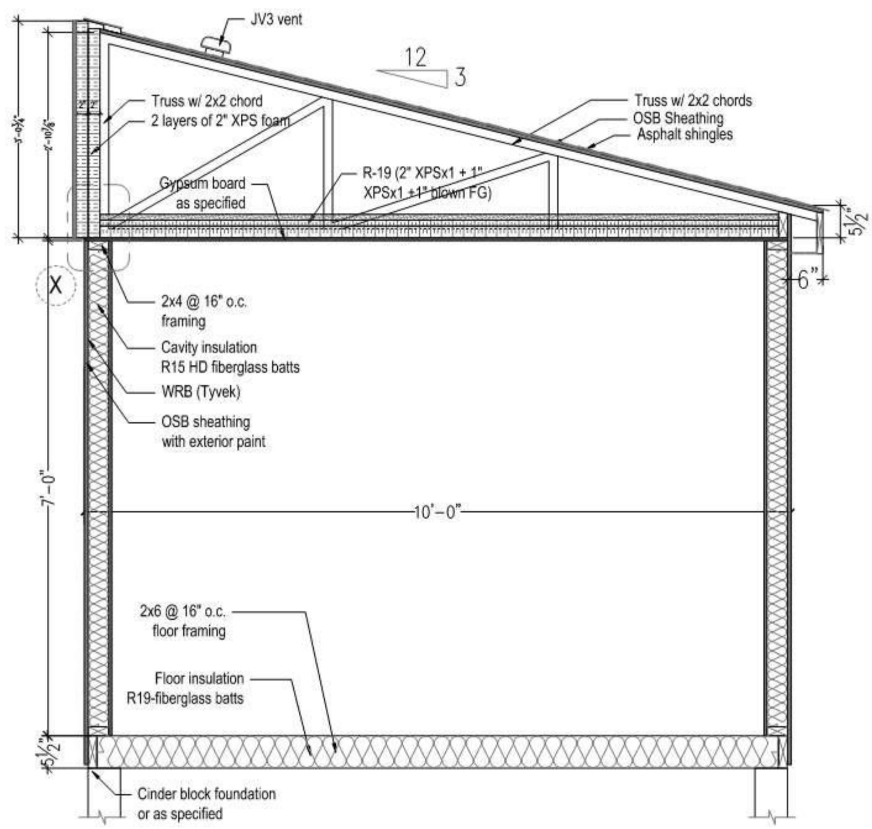
The testing apparatus was a single section manufactured home structure measuring approx. 10 feet wide and 16 feet long (Figure 134). A full scale shed-roof (slope 3:12) will be built and placed over 7-foot-high walls (Figure 135 to Figure 137) for sections of the unit). The roof was divided into seven bays with five central bays each about 2'-9" in width. The end bays, each about 1 foot wide, served as buffer zones ensuring similar thermal boundaries between the experimental design bays. Attic insulation levels in all bays were identical. Except for width, the buffer bays were identical to the base case design. Each design bay was isolated (from a moisture and thermal flow standpoint) from adjacent bays by means of an insulated partition wall and air sealing.

Figure 134: Test Apparatus - Plan



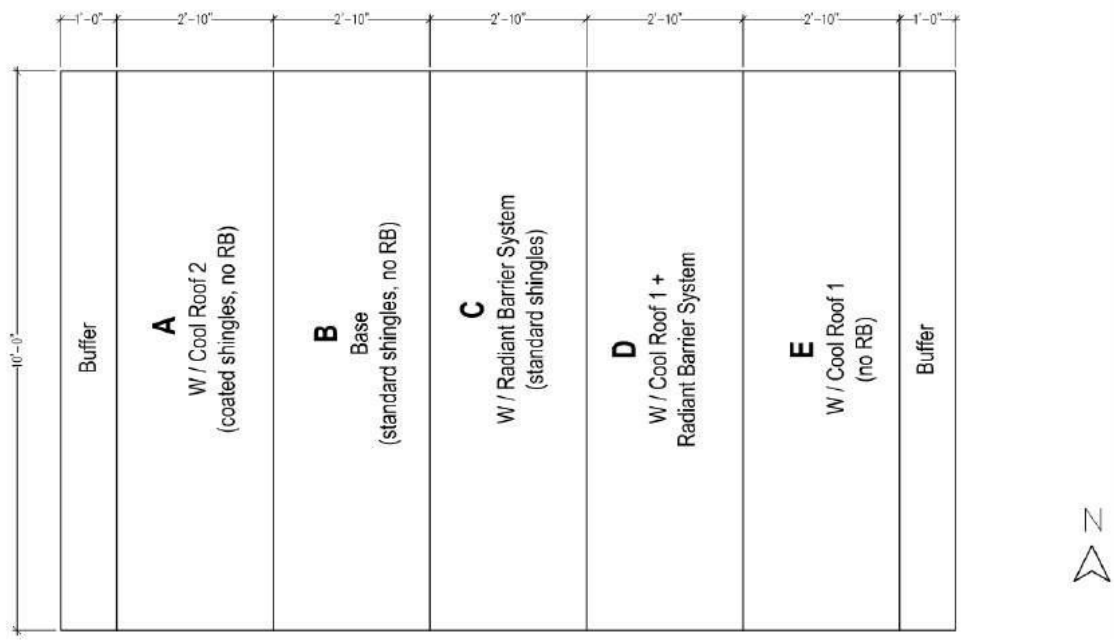
Source: The Levy Partnership, Inc.

Figure 135: Test Apparatus - Cross Section



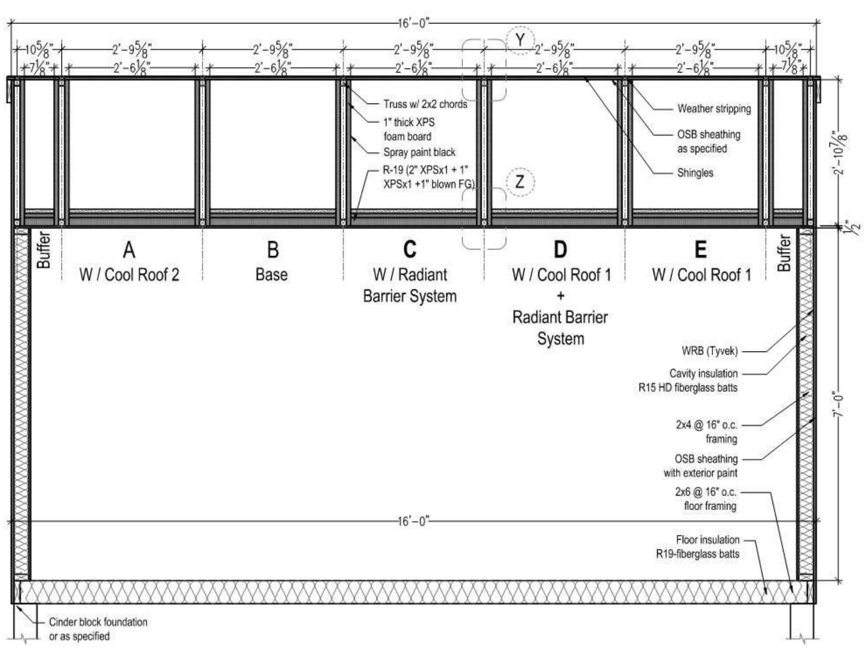
Source: The Levy Partnership, Inc.

Figure 136: Schematic Layout of Roof Configurations



Source: The Levy Partnership, Inc.

Figure 137: Test Apparatus: Longitudinal Section



Source: The Levy Partnership, Inc.

Table 35: Materials Supply List

Product brand name	Product description	Supplier	Quantity
INSULATION MATERIALS			
Wall	R-15 HD FG batts Kraft faced	Owens Corning	400 sqft *(364 sqft)*
Floor	R-19 FG batts Kraft faced	Owens Corning	200 sqft *(160 sqft)*
Attic (original order)	R-19 FG batts Unfaced	Owens Corning	200 sqft *(131.86 sqft)*
Attic (additional order)	Foamular XPS 2”	Owens Corning	15 panels @ 4’x8’
Thermal barrier	Foamular XPS 1”	Owens Corning	400 sqft *(323.93 sqft)*
VENTILATION PRODUCTS			
Mushroom vent	J-vent – JV3	FAMCO	9
COOL ROOF PRODUCTS			
Cool roof asphalt shingles *(Cool Roof Type 1)*	Duration Premium Harbor Fog Duration Premium Sage	Owens Corning	100 sqft each *(60.67 sqft -2 bays)*
Acrylic coating - field applied on standard shingles *(Cool Roof Type 2)*	TopGard 4000 acrylic coating	Johns Manville	Base coat – 5 gal. bucket Top coat – 5 gal. bucket *(30.33 sqft)*
ASSOCIATED EQUIPMENT			
Cool Roof Type 2	Brushes and paddle mix	Any	1 - 2

Source: The Levy Partnership, Inc.

The interior of the house was an open layout with no partition walls. There was one door and no windows. Walls and floors were built and insulated as per specifications in Chapter 4.

The roof was subject to long-term monitoring and assessment with sensors installed to monitor temperature and heat flux within the roof cavities. Temperature inside the living space was controlled. Temperature set points were controlled remotely via a data logger.

The experimental sections of the roof were instrumented with temperature and heat flux sensors for thermal performance testing and monitoring over a cooling season.

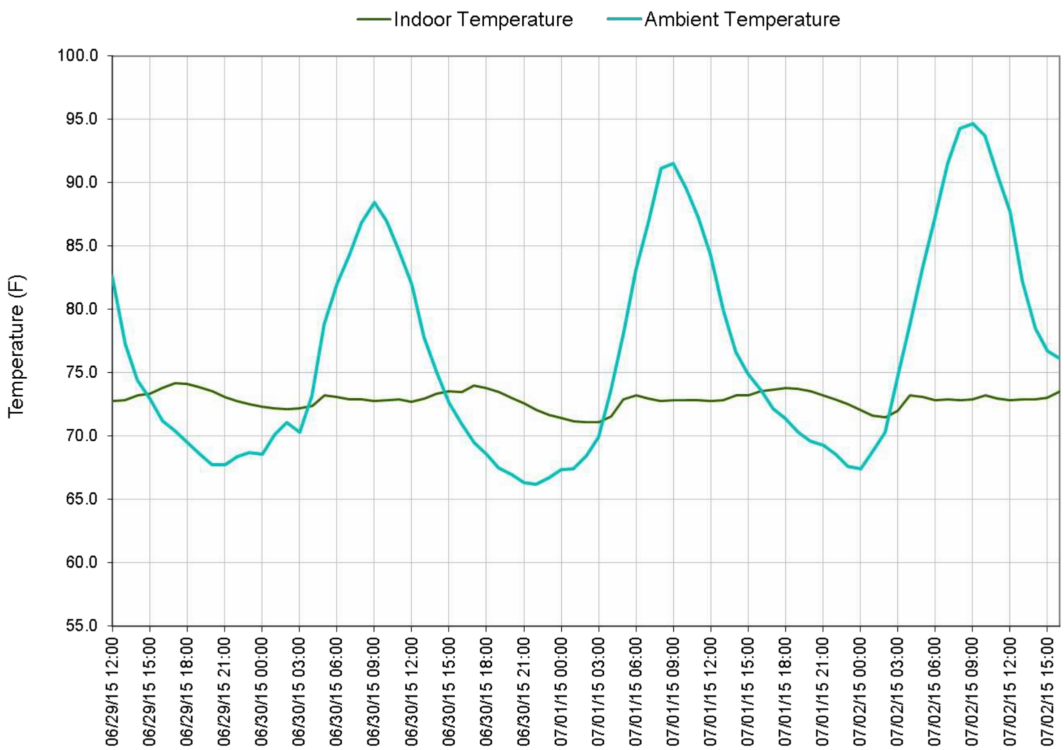
Results

Weather Data and Interior Conditions

The on-site weather station measured 1,076 cooling degree days for the cooling period (5/15/2015 to 8/24/2015). TMY3 data for Palm Springs (a nearby TMY3 weather station) shows 3,693 cooling degree days for the same annual period. Although weather conditions in Riverside and Palm Springs are different, Palm Springs was chosen for use in the energy-savings analyses because of its availability of TMY3 data. (Other locations with less drastically hot cooling periods were also analyzed.) Average onsite wind speed and insolation at Riverside over the cooling analysis period was 0.89 mph and 26.5 W/ft^2, respectively; precipitation was not recorded.

The temperature and relative humidity of the interior space of the test house were maintained between 71-74°F, as shown in Figure 138 while outside temperatures ranged well beyond these measurements.

Figure 138: Indoor Conditions in Test Assembly



Source: The Levy Partnership, Inc.

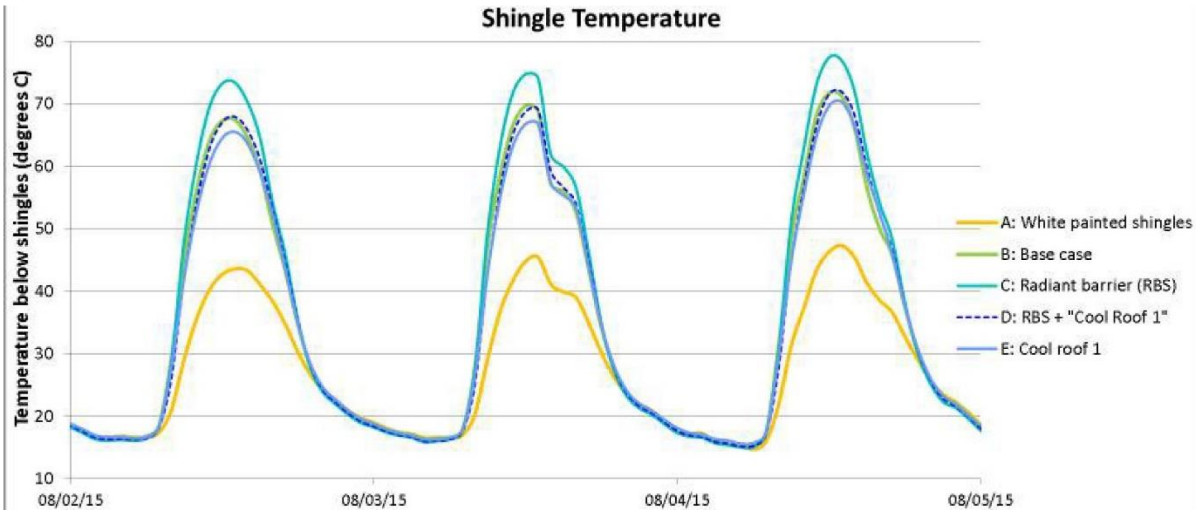
Temperature Analysis in Test Assemblies

While the test bays shared interior, below-ceiling conditions, they did not communicate within the ceiling. Each assembly had a signature temperature profile just below the shingles, as shown in Figure 139. Most of the assemblies show patterns similar to the base case (bay B), but the white-painted shingles remained significantly cooler (up to 20˚F cooler), which could bode well for roof durability in addition to energy savings. Sometimes the roof with the radiant barrier had higher peak temperatures, possibly due to retention of the heat within the roof sheathing.

Heat Flux at Test Bays

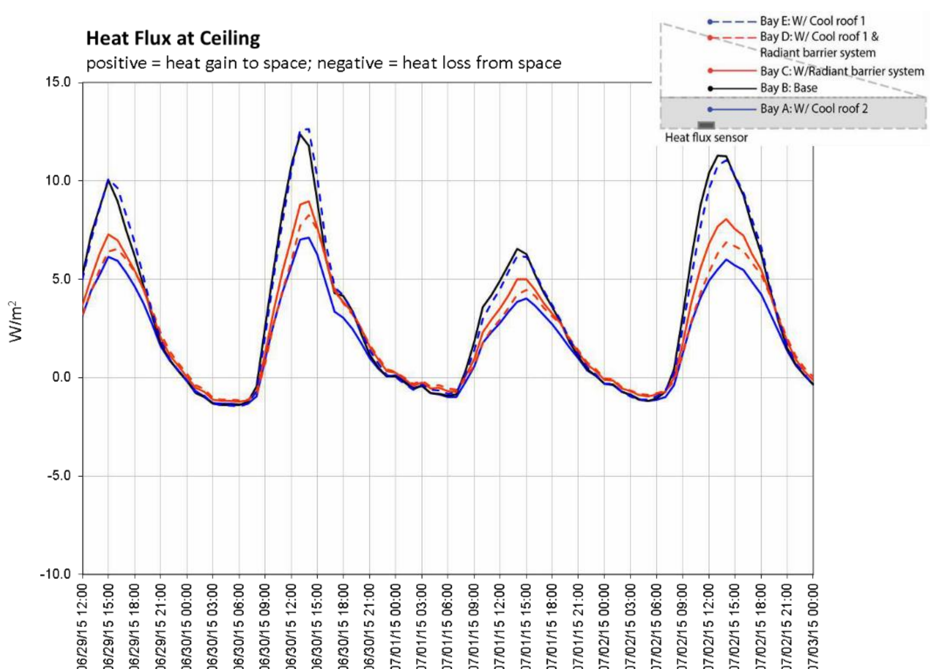
The heat flux across the ceiling varied between the roof types as well (Figure 140). At lower temperatures (and during times of the day with less sun exposure), the ceilings of all test assemblies showed similar heat flux measurements; however, during the middle of the day, the base case and "Cool Roof 1" demonstrated the highest heat gain through the ceiling, while "Cool Roof 2" with the white-painted shingles showed the least heat gain. The radiant barrier appears to have some effect on heat flux, but not as significant an effect as do the white-painted shingles.

Figure 139: Shingle Temperature at each Test Bay



Source: The Levy Partnership, Inc.

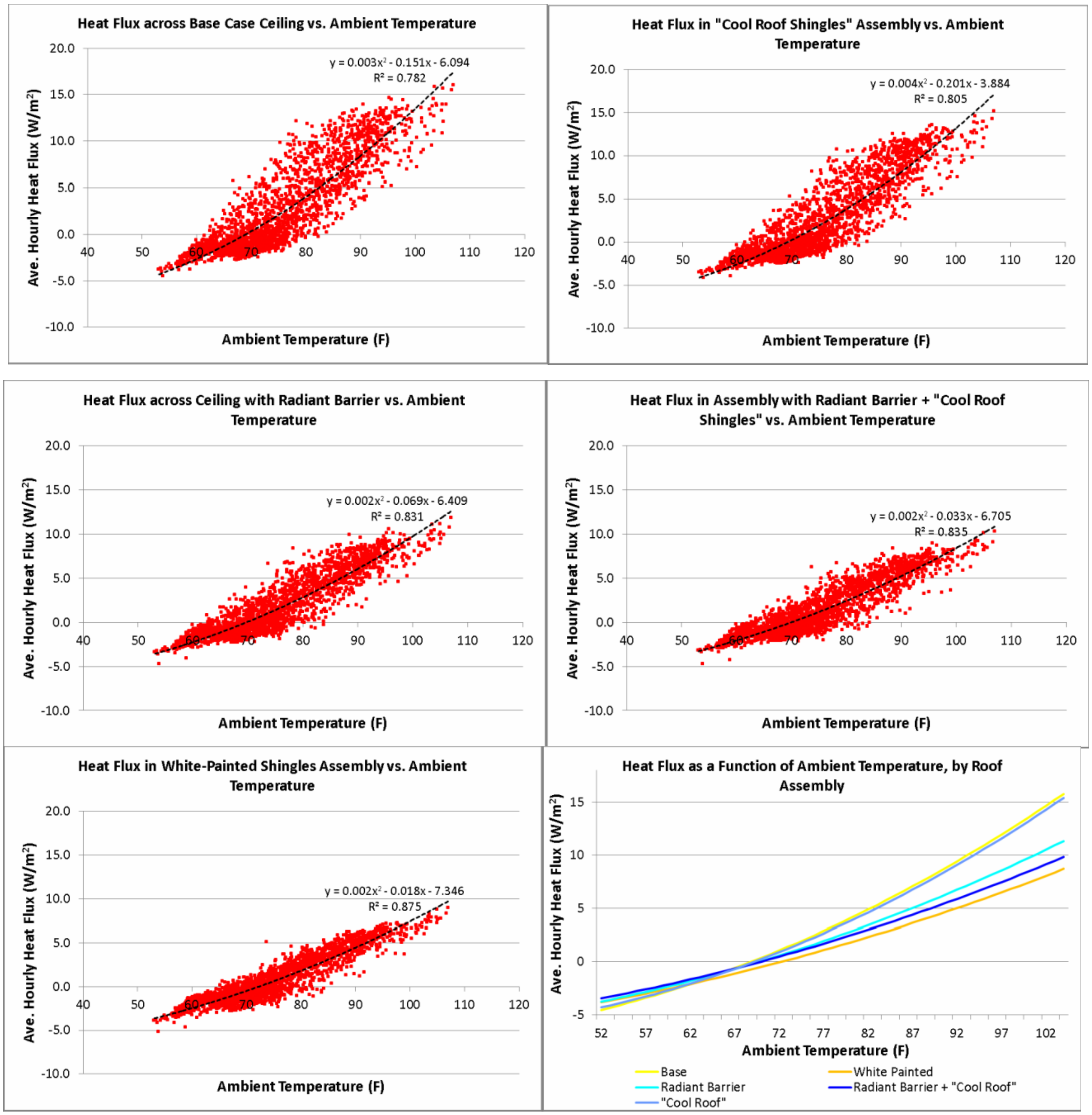
Figure 140: Heat Flux at Ceiling of each Assembly



Source: The Levy Partnership, Inc.

Heat flux through the ceiling was plotted as a function of ambient temperature for each assembly for the measurement period (Figure 141). Polynomial regressions were used to formulate equations for relating heat flux to ambient temperature. This was also done using both ambient temperature and solar radiation as independent variables, but it became evident that solar radiation did not significantly improve the R^2 value (R^2 = 0.80 both with and without solar radiation considered), and the coefficients for solar radiation were magnitudes smaller than those for ambient temperature; therefore, only temperature was used for the sake of simplicity. The best-fit equations for each cool-roof assembly are shown together.

Figure 141: Heat Flux as a Function of Ambient Temperature



Source: The Levy Partnership, Inc.

Analysis

In order to estimate the energy savings from each cool-roof assembly, the polynomial regressions were applied to TMY3 weather data in various California locations. Several assumptions were made to calculate energy savings. A standard 56-foot-long, double-wide (27.3

feet wide) home was assumed, although the savings can be calculated proportionately to any size home. A 14 SEER heat pump and 5 percent duct losses were also assumed. The cooling period was taken as May through October. Heating penalty (the excess heat required due to less heat absorption through the cool-roof assemblies) was also calculated for winter months, but its effect was negligible at a maximum of $0.40 annually. However, limitations may exist in this analysis of heating-season data because the data was collected primarily during the cooling season, during which there was little severe heat loss through the ceiling. In order to capture true heating-season energy penalties, data should be collected during the heating season.

Table 36 and Table 37 summarize the expected energy savings for each cool-roof assembly in different California climates.

Table 36: Annual Cooling Season Cool Roof Energy Bill Savings

Annual energy savings (kWh/yr)	Base	Cool Roof 1 (cool shingles)	RBS only	Cool Roof 1 + RBS	Cool Roof 2 (White paint)
	Bay B	*Bay E*	*Bay C*	*Bay D*	*Bay A*
Palm Springs, CA		28	329	450	568
Redding, CA		17	151	205	277
Needles, CA		29	381	521	647
Imperial, CA		27	324	442	558
Bakersfield, CA		19	167	227	310
Note: All savings are relative to the base case. Savings are for summertime only and assume 14-SEER cooling equipment. *Fuel rate: $0.18/kWh*					

Source: The Levy Partnership, Inc.

Table 37: Annual Cooling Season Cool Roof Energy Savings

Annual energy savings ($/yr)	Base	Cool Roof 1 (cool shingles)	RBS only	Cool Roof 1 + RBS	Cool Roof 2 (White paint)
	Bay B	*Bay E*	*Bay C*	*Bay D*	*Bay A*
Palm Springs, CA		$ 4.99	$ 59.27	$ 80.99	$ 102.18
Redding, CA		$ 3.00	$ 27.12	$ 36.86	$ 49.86
Needles, CA		$ 5.26	$ 68.50	$ 93.71	$ 116.33
Imperial, CA		$ 4.85	$ 58.22	$ 79.56	$ 100.37
Bakersfield, CA		$ 3.48	$ 30.03	$ 40.79	$ 55.78
Note: All savings are relative to the base case. Savings are for summertime only and assume 14-SEER cooling equipment. *Fuel rate: $0.18/kWh*					

Source: The Levy Partnership, Inc.

As expected, energy savings is higher in hotter climates. Significant energy savings can be gleaned from the white-painted shingles, as well as, in some cases, the radiant barrier, both with and without the "cool shingles." The "cool shingles" alone, however, do not appear to efficiently reduce energy bills, perhaps because they simply are not reflective enough.

Inferences and Recommendations

The data indicate that different cool-roof assemblies yield different heat gain/loss, as well as temperature patterns at different locations throughout the roof. Based on the location, style, and construction of the home, highly reflective shingles or a radiant barrier may be an energy- and cost-effective measure.

Several limitations exist in this analysis, including that a cost-benefit analysis cannot yet be properly performed given that techniques for constructing "Cool Roof 2" with the highly reflective shingles have not yet been perfected in the manufacturing plant, and painting shingles in the plant would disrupt the assembly line. Additionally, reported savings are based on TMY3 weather data gathered from 1991 to 2005, which does not account for climate change and thus rising temperatures in California desert regions, so savings may prove to be higher than reported here.

Next steps in implementing different cool-roof configurations in the factory-built housing industry would be to analyze how each construction fits within the factory-building process. Can more reflective shingles be made as standard and stocked? What is their cost premium? It would also be worthwhile testing whether a radiant barrier system would augment the energy savings of more reflective roof shingles. In other words, would it be worthwhile to combine the techniques used in bays A and C – similar to what was done in bay D? California's Title 24 2013 Building Energy Efficiency Standards currently requires homes in certain climate zones using the prescriptive requirements to have both high roof reflectance and a radiant barrier, but never just a cool roof. Perhaps this research could also be used to inform future versions of the Title 24 requirements in terms of payback for using different combinations of cool-roof methods in warmer climates.

CHAPTER 7:
Energy Analysis and Other Impacts

This chapter provides analysis demonstrating the energy, environmental and economic benefits associated with state-wide adoption of the advanced envelope technologies by manufactured home builders. The environmental analysis presented in this section is based on computer simulation data. Economic impact presented includes cost benefit projections as well as statewide benefit evaluations over the next few years.

Impact of Advanced Envelope Technologies on Energy and Environment

Project Energy Savings

To examine the impact of the advanced technologies on energy and environment, whole-house building simulation[11] and impact analysis was conducted. The Advanced Envelope design was compared against a Base Case reflective of current building practice. A summary of selected energy specifications of the Base and Advanced models is provided in Table 38.

Table 38: Input Summary Table

Components	Base Case	Advanced Envelope Design
Floor**	R-11 FG blanket	R-22 FG blanket
Wall	R-11 FG batts	R-13 FG batts + R-10 continuous exterior insulation
Ceiling	R-19 Standard density blown FG	R-49 blown FG - dense packed at eaves, standard density in the field
Infiltration	9.0 air changes per hour (ACH)	3.0 ACH
Cool Roofs	No	Yes/No*
Radiant Barrier	No	Yes/No*

* **Cool roofs and radiant barriers are assumed to be installed only in locations where the technology will reduce energy use.**
**** One of the assumptions made with the advanced technologies is that the industry is likely to implement a better floor assembly than the baseline when embracing the advanced wall and roof assemblies.**

Source: The Levy Partnership, Inc.

The advanced envelope design also includes a cool roof and an attic radiant barrier. A cool roof is designed to reflect more sunlight and absorb less heat than a standard roof by means of white or highly reflective paint, sheet covering, or highly reflective tiles or shingles. A radiant

[11] Energy modeling was conducted with CBECC Residential tool; one of Energy Commission's approved computer program software. This tool is also widely used to establish compliance with California's Title 24 code for thermal performance of buildings.

barrier is a thin sheet of reflective material, often aluminum, applied to a substrate such as Kraft paper, plastic film, cardboard, or plywood and installed over unconditioned attics, to primarily reduce summer heat gain and cooling costs. However, they are not appropriate for all climates as they can increase energy costs in heating dominated climates with low cooling loads.

A home of 28' X 60' was modeled in sixteen locations that are representative of California's climate zones. The design assumptions made for the energy simulation are presented in Table 39.

Table 39: Detailed House Specifications

Components	Design assumptions
Home size	28' X 60' double-section
Floor area	1680 sq. ft.
Window area	12 % of floor area
Window	U = 0.68, SHGC = 0.65
Door	U = 0.5
Heating system	Gas/Electric forced air furnace, Gas furnace AFUE: 78%
Cooling system	Split air conditioner SEER: 13, EER: 11.3
Space-conditioning distribution	Metal ducts sealed with mastic, R-6 crossover duct in crawl space
Ventilation	Whole-house fan, continuous
Domestic hot water	Electric water heater Energy Factor: 0.97
Appliances and miscellaneous	Standard refrigerator, Dishwasher, Clothes washer, Clothes dryer, Cooking appliances

Source: The Levy Partnership, Inc.

The benefits of implementing the advanced envelope design in gas heated homes and electric heated homes in California can be seen in Table 40 and Table 41, respectively. As noted above, cool roof technologies are only considered in locations and for energy types where they provide benefit.

The climate zone and type of heating system (gas or electric) are crucial in determining the annual energy and cost savings. The energy cost savings in gas heated homes range from $22 to $338 when compared to the baseline home. The energy cost savings for electric heated homes are more substantial, ranging from $44 to $848. Thus, the advanced assemblies have a significant impact on the energy consumption of manufactured homes, reducing the dollars spent each year on energy bills by up to 33 percent in gas heated homes and 40 percent in electric heated homes.

Greenhouse Gas Emission Reductions

Greenhouse gases such as carbon dioxide, methane, nitrous oxide, fluorinated gases and chlorofluorocarbons, trap solar heat in the earth's atmosphere and are a cause for global climate change. These gases are typically expressed in carbon dioxide equivalent.

Table 40: Energy Savings with Advanced Envelope Technologies in Gas-heated Homes

Location	Base case				Advanced envelope technologies				Savings ($/yr)
	Heating	Cooling	Fans	Total	Heating	Cooling	Fans	Total	
	kWh/yr			$/yr	kWh/yr			$/yr	
CZ1 Arcata*	344	0	398	$516	173	0	251	$269	**$247**
CZ2 Santa Rosa*	179	283	256	$328	85	238	175	$184	**$144**
CZ3 Oakland*	151	16	231	$239	63	14	156	$111	**$128**
CZ4 San Jose	133	410	216	$284	67	233	160	$158	**$126**
CZ5 Santa Maria*	127	1	211	$202	39	4	136	$76	**$126**
CZ6 Torrance	39	276	135	$124	14	178	114	$70	**$53**
CZ7 San Diego	9	186	110	$65	2	129	103	$44	**$22**
CZ8 Fullerton	31	741	128	$196	12	375	112	$103	**$93**
CZ9 Burbank	53	1,138	147	$300	23	656	122	$170	**$130**
CZ 10 Riverside	58	1,453	152	$364	26	843	124	$207	**$157**
CZ 11 Red Bluff	200	2,422	273	$742	112	1,622	198	$472	**$270**
CZ 12 Sacramento	194	1,060	268	$489	115	545	200	$282	**$207**
CZ 13 Fresno	173	2,616	251	$739	103	1,712	190	$475	**$265**
CZ 14 Palmdale	183	2,309	259	$698	97	1,542	185	$435	**$263**
CZ 15 Palm Springs	15	6,565	115	$1,222	4	4,770	106	$883	**$338**
CZ 16 Blue Canyon*	483	331	516	$775	285	316	346	$487	**$289**

U.S Energy Information Administration tabulates the utility costs for California state as of September 2016 as $1.29/therm and $0.18/kWh. These values are used to estimate the cost impacts.

***Cool roofs and radiant barriers should not be installed in these climate zones**

Source: The Levy Partnership, Inc.

Table 41: Energy Savings with Advanced Envelope Technologies in Electric-heated Homes

Location	Base case				Advanced envelope technologies				Savings ($/yr)
	Heating	Cooling	Fans	Total	Heating	Cooling	Fans	Total	
	kWh/yr			$/yr	kWh/yr			$/yr	
CZ1 Arcata*	7,865	0	398	$1,487	3,959	0	251	$758	**$730**
CZ2 Santa Rosa*	4,087	283	256	$833	1.938	235	175	$423	**$410**
CZ3 Oakland*	3,445	16	231	$665	1,432	14	156	$288	**$376**
CZ4 San Jose*	3,304	410	216	$707	1,217	374	148	$313	**$394**
CZ5 Santa Maria*	2,904	1	211	$561	898	4	136	$187	**$374**
CZ6 Torrance*	884	276	135	$233	208	287	110	$109	**$124**
CZ7 San Diego	213	186	110	$92	34	129	103	$48	**$44**
CZ8 Fullerton	705	741	128	$283	279	375	112	$138	**$145**
CZ9 Burbank	1,211	1,138	147	$449	534	656	122	$236	**$213**
CZ 10 Riverside	1,325	1,453	152	$527	585	843	124	$279	**$248**
CZ 11 Red Bluff	4,560	2,422	273	$1,306	2,561	1,622	198	$789	**$517**
CZ 12 Sacramento*	4,431	1,060	268	$1,037	2,304	796	189	$592	**$445**
CZ 13 Fresno	3,958	2,616	251	$1,229	2,344	1,712	190	$764	**$464**
CZ 14 Palmdale	4,175	2,309	259	$1,214	1,798	1,844	170	$690	**$524**
CZ 15 Palm Springs	343	6,565	115	$1,264	99	4,770	106	$896	**$369**
CZ 16 Blue Canyon*	11,449	331	102	$2,139	6,510	316	346	$1,291	**$848**

U.S Energy Information Administration tabulates the utility costs for California state as of September 2016 as $1.29/therm and $0.18/kWh. These values are used to estimate the cost impacts

***Cool roofs and radiant barriers provide not energy benefit and should not be used in these climate zones**

Source: The Levy Partnership, Inc.

Through the energy simulation, greenhouse gas emissions were quantified for the Base case as well as the Advanced assembly case to compare and calculate the savings. These greenhouse gas emission rates are based on energy equivalents established by Energy Commission as 0.83 lbs/kWh for electricity and 11.7 lbs/therm for natural gas use. The results are provided for the sixteen representative locations in each of California's climate zones. These carbon dioxide emission savings are based on the energy impacts discussed in the previous section and are summarized in Table 42 and Table 43.

Table 42: CO2 Emission Savings with Advanced Envelope Technologies in Gas-heated Homes

Location	Base case			Advanced envelope technologies			CO_2 emission savings
	(therms/yr)	(kWh/yr)	(lbs/yr)	(therms/yr)	(kWh/yr)	(lbs/yr)	(lbs/yr)
CZ1 Arcata*	344	398	4,357	173	251	2,235	**2,122**
CZ2 Santa Rosa*	179	539	2,541	103	313	1463	**1,078**
CZ3 Oakland*	151	247	1,968	63	170	874	**1,094**
CZ4 San Jose	133	626	2,073	67	393	1,115	**958**
CZ5 Santa Maria*	127	212	1,663	39	140	576	**1,087**
CZ6 Torrance	39	411	794	14	292	405	**389**
CZ7 San Diego	9	296	354	2	232	210	**144**
CZ8 Fullerton	31	869	1,082	12	487	547	**535**
CZ9 Burbank	53	1,285	1,687	23	778	918	**769**
CZ 10 Riverside	58	1,605	2,011	26	967	1,102	**909**
CZ 11 Red Bluff	200	2,695	4,571	112	1,820	2,822	**1,749**
CZ 12 Sacramento	194	1,328	3,370	115	745	1,959	**1,411**
CZ 13 Fresno	173	2,867	4,406	103	1,902	2,779	**1,627**
CZ 14 Palmdale	183	2,568	4,269	97	1,727	2,562	**1,707**
CZ 15 Palm Springs	15	6,680	5,720	4	4,876	4,099	**1,621**
CZ 16 Blue Canyon*	483	847	6,353	249	662	3,462	**2,891**
Greenhouse gas emission rates are based on Energy Commission established energy equivalents and equal to 0.83 lbs./kWh and 11.7 lbs./therm for electricity and natural gas use reductions, respectively ***Cool roofs and radiant barriers are assumed <u>not</u> be installed in these climate zones**							

Source: The Levy Partnership, Inc.

Table 43: CO2 Emission Savings with Advanced Envelope Technologies in Electric-heated Homes

Location	Base case			Advanced envelope technologies			CO_2 emission savings
	(therms/yr)	(kWh/yr)	(lbs/yr)	(therms/yr)	(kWh/yr)	(lbs/yr)	(lbs/yr)
CZ1 Arcata*	n/a	8,263	6,858	n/a	4,210	3,494	**3,364**
CZ2 Santa Rosa*	n/a	4,626	3,840	n/a	2,351	1,951	**1,889**
CZ3 Oakland*	n/a	3,692	3,064	n/a	1,602	1,330	**1,734**
CZ4 San Jose*	n/a	3,930	3,262	n/a	1,739	1,443	**1,819**
CZ5 Santa Maria*	n/a	3,116	2,586	n/a	1,038	862	**1,724**
CZ6 Torrance*	n/a	1,295	1,075	n/a	605	502	**573**
CZ7 San Diego	n/a	509	422	n/a	266	221	**201**
CZ8 Fullerton	n/a	1,574	1,306	n/a	766	636	**670**
CZ9 Burbank	n/a	2,496	2,072	n/a	1,312	1,089	**983**
CZ 10 Riverside	n/a	2,930	2,432	n/a	1,552	1,288	**1,144**
CZ 11 Red Bluff	n/a	7,255	6,022	n/a	4,381	3,636	**2,386**
CZ 12 Sacramento*	n/a	5,759	4,780	n/a	3,289	2,730	**2,050**
CZ 13 Fresno	n/a	6,825	5,665	n/a	4,246	3,524	**2,141**
CZ 14 Palmdale*	n/a	6,743	5,597	n/a	3,812	3,164	**2,433**
CZ 15 Palm Springs	n/a	7,023	5,829	n/a	4,975	4,129	**1,700**
CZ 16 Blue Canyon*	n/a	11,882	9,862	n/a	7,172	5,953	**3,909**
Greenhouse gas emission rates which are drawn from are 0.83 lbs/kWh and 11.7 lbs/therm for electricity and natural gas respectively ***Cool roofs and radiant barriers should not be installed in these climate zones**							

Source: The Levy Partnership, Inc.

The greenhouse gas emission savings from using advanced envelope technologies range from 144 lbs/yr to 2,891 lbs/yr relative to the baseline home in gas heated homes and from 201 lbs/yr to 3,909 lbs/yr relative to the baseline home in electric heated homes. Thus, the advanced assemblies show a noteworthy impact on reducing carbon emissions, by reducing emissions by up to 45 percent in gas heated homes and up to 40 percent in electric heated homes in a year.

Non-Energy Benefits

In addition to the energy, environmental and cost benefits, the advanced technologies also offer the following benefits:

- **Downsizing of mechanical equipment**: The advanced envelope solutions will result in a ½ to 1 ton average cooling capacity reduction per home.[12] This implies lower first cost of the cooling equipment, a reduction in demand and better sizing to meet the lower load.
- **Reduced Noise**: The advanced wall system incorporates a continuous layer of exterior insulation on the wall sheathing with generally higher insulation levels throughout. These improvements result in greater attenuation of external noise. For homebuyers, it is a quieter home.
- **Improved Indoor Environment**: Reducing infiltration by using continuous external insulation on the walls will provide greater control of indoor air quality resulting in a healthier environment and reduced chance of moisture problems.
- **Resale value**: Homes built with advanced technologies are likely to increase in value relative to current construction as future buyers will invariably place a better value on energy use and efficiency and energy costs in their buyer decisions.

Economic Impact of Advanced Envelope Technologies

Energy Costs

This section focuses on the net economic benefit of the advanced assemblies to a customer of a manufactured home. The analysis accounts for both the incremental first cost incurred due to implementation of more energy efficient, advanced assemblies and the monthly energy savings achieved during home occupancy. The advanced technologies engender a high initial cost, both in raw material cost and, in some cases, added labor. For instance, foam board is more expensive than fiberglass batt insulation and requires additional steps to install slowing production. By taking the full spectrum of costs into consideration, this analysis considers the full impact of the measures on affordability for the purchaser.

The goal of this assessment was to quantify the benefits of the measures and assess if, from a cost standpoint, if they outweighed the costs. A positive benefit for the homebuyer translates into a prudent purchase the basis of a compelling sales message. Where a net positive benefit is not achieved, financial incentives could help drive the implementation of the technologies that otherwise yield a societal benefit.

The analysis is based on the assumptions listed on Table 44. Note that these assumptions are based on current market conditions and will change over time.

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[12] *"Manufactured Home Cooling Equipment Sizing Guidelines for ENERGY STAR® Qualified Manufactured Homes and Homes Built to the HUD Standards."* Manufactured Housing Research Alliance (now SBRA), New York, NY, 2005.

Table 44: Assumptions in Measuring the Economic Impact on Manufactured Homebuyers

Down Payment	10%
Mortgage Interest Rate	9%
Mortgage Period	20 years
Occupancy Term	35 years
Principal Recapture Rate	0%

Source: The Levy Partnership, Inc.

Table 45 and Table 46 show the net benefit/cost associated with the implementation of the advanced assembly in gas-heated and electric-heated homes, respectively. The calculation is shown for sixteen locations in California, representative of the state's climate zones.

Table 45: Cost-benefit Analysis of Advanced Envelope Technologies in Gas-heated Homes

Location	Increase in Home Cost	Down Payment	Inc. in Mortgage	Inc. in Monthly Mort. pay	Energy savings ($/mth.)	Total mort. pay. (Discounted Present Value)	Total Energy Savings	Net Benefit (Cost)
CZ1 Arcata	$2,671	$267	$2,404	$22	$26	$3,861	$10,837	$6,708
CZ2 Santa Rosa	$2,671	$267	$2,404	$22	$13	$3,861	$5,443	$1,315
CZ3 Oakland	$2,671	$267	$2,404	$22	$11	$3,861	$4,694	$566
CZ4 San Jose	$2,671	$267	$2,404	$22	$11	$3,861	$4,612	$483
CZ5 Santa Maria	$2,671	$267	$2,404	$22	$11	$3,861	$4,612	$483
CZ6 Torrance	$2,671	$267	$2,404	$22	$5	$3,861	$2.092	($2,037)
CZ7 San Diego	$2,671	$267	$2,404	$22	$3	$3,861	$1,243	($2,885)
CZ8 Fullerton	$2,671	$267	$2,404	$22	$13	$3,861	$5,402	$1273
CZ9 Burbank	$2,671	$267	$2,404	$22	$11	$3,861	$4,694	$566
CZ 10 Riverside	$2,671	$267	$2,404	$22	$15	$3,861	$6,267	$2,138
CZ 11 Red Bluff	$2,671	$267	$2,404	$22	$29	$3,861	$12,063	$7,935
CZ 12 Sacramento	$2,671	$267	$2,404	$22	$21	$3,861	$8,753	$4,625
CZ 13 Fresno	$2,671	$267	$2,404	$22	$28	$3,861	$11,668	$7,540
CZ 14 Palmdale	$2,671	$267	$2,404	$22	$27	$3,861	$11,257	$7,128
CZ 15 Palm Springs	$2,671	$267	$2,404	$22	$34	$3,861	$14,180	$10,051
CZ 16 Blue Canyon	$2,671	$267	$2,404	$22	$30	$3,861	$12,500	$8,371

Source: The Levy Partnership, Inc.

Table 46: Cost-benefit Analysis of Advanced Envelope Technologies in Electric-heated Homes

Location	Increase in Home Cost	Down Payment	Inc. in Mortgage	Inc. in Monthly Mort. pay	Energy savings ($/mth.)	Total mort. pay. (Discounted Present Value)	Total Energy Savings	Net Benefit (Cost)
CZ1 Arcata	$2,671	$267	$2,404	$22	$61	$3,861	$25,550	$21,422
CZ2 Santa Rosa	$2,671	$267	$2,404	$22	$34	$3,861	$14,350	$10,222
CZ3 Oakland	$2,671	$267	$2,404	$22	$31	$3,861	$13,160	$9,032
CZ4 San Jose	$2,671	$267	$2,404	$22	$33	$3,861	$13,790	$9,662
CZ5 Santa Maria	$2,671	$267	$2,404	$22	$31	$3,861	$13,090	$8,962
CZ6 Torrance	$2,671	$267	$2,404	$22	$10	$3,861	$4,340	$212
CZ7 San Diego	$2,671	$267	$2,404	$22	$4	$3,861	$1,540	($2,588)
CZ8 Fullerton	$2,671	$267	$2,404	$22	$12	$3,861	$5,075	$947
CZ9 Burbank	$2,671	$267	$2,404	$22	$18	$3,861	$7,455	$3,327
CZ 10 Riverside	$2,671	$267	$2,404	$22	$21	$3,861	$8,680	$4,552
CZ 11 Red Bluff	$2,671	$267	$2,404	$22	$43	$3,861	$18,095	$13,967
CZ 12 Sacramento	$2,671	$267	$2,404	$22	$37	$3,861	$15,575	$11,447
CZ 13 Fresno	$2,671	$267	$2,404	$22	$39	$3,861	$16,240	$12,112
CZ 14 Palmdale	$2,671	$267	$2,404	$22	$44	$3,861	$18,340	$14,212
CZ 15 Palm Springs	$2,671	$267	$2,404	$22	$31	$3,861	$12,915	$8,787
CZ 16 Blue Canyon	$2,671	$267	$2,404	$22	$71	$3,861	$29,680	$25,552

Source: The Levy Partnership, Inc.

The advanced assemblies increase the cost of a home by an estimated $2,671 due to the insulation material cost and its associated expenses, such as longer fasteners for the walls and the required ventilation baffles for the roof. This increases the mortgage payment per month. However, the improved energy efficiency of the home also leads to substantial energy savings of up to $34 a month in gas heated homes and up to $71 a month in electric heated homes.

Over the occupancy period of 35 years (expected life of home), almost all cities achieve a net benefit, up to $10,051for gas heated homes and $25,552 for electric heated homes. In cities where a net benefit is not realized, incentives may be needed to help motivate customers adopt the proposed advanced assemblies.

Economic Development and Statewide Benefits

This section discusses the statewide economic impact of the advanced technologies on the manufactured housing industry over the next few years. To project the impact of the advanced technologies, it is valuable to consider the size of the factory built housing market today and estimates for the future. According to Market statistics data of 20 years from a survey conducted by Sawtooth Research Group, Inc., the average annual number of manufactured homes built and sold in California is 10,000.

A robust marketing effort that includes demonstrating that the Advanced Envelope measures yield a positive economic benefit for the buyer, are the catalysts for transforming the market. The marketing effort is underway. Having demonstrated the ease of adopting the measures into plan production will facilitate this process.

To estimate the economic impact, projections of market acceptance of the technologies are considered. These projections are conservative given the investment in marketing, retooling, reengineering, code filings and product design changes that will be required. Market transformation is estimated to be characterized by the following three stages of acceptance:

- Early adopters: By 2020, industry leaders take the research products to market. This is projected to impact about 10 percent of all new homes built.
- Major market movers: By 2022, the center of the market embraces the technology, mainly producers of homes at the higher end of the first cost spectrum. The technology is being perfected during the intervening years and the costs of the technology are declining. Total participation will reach about 40 percent of all new homes built.
- Market laggards: By 2025, with demonstrated cost benefits, the technology becomes standard practice. Most, if not all, manufacturers embrace the new designs. Participation rate is assumed to reach 80 percent.

Based on these projections, the cumulative energy and environmental impacts of the advanced assemblies at each market stage for gas heated homes and electric heated homes respectively are shown Table 47 and Table 48.

By 2025, implementing the advanced assemblies statewide is projected to achieve energy cost savings of $18,755,625 for gas heated homes and $40,641,125 for electric heated homes.

Table 47: Cumulative Impacts from Time of Commercialization (2017), Gas-heated Homes

Average Market Saturation	Through Year	Electric Savings (kWh/year)	Gas Savings (therms/year)	Carbon Emission Savings (tons)	Cost Savings ($)
10%	2020	2,486,250	432,000	3,417	1,071,750
40%	2022	7,351,750	1,728,000	13,670	4,287,000
80%	2025	40,916,125	7,560,000	59,805	18,755,625
Impacts are cumulative for all homes built and sold through the year indicated.					

Source: The Levy Partnership, Inc.

Table 48: Cumulative Impacts from Time of Commercialization (2017), Electric-heated Homes

Average Market Saturation	Through Year	Electric Savings (kWh/year)	Carbon Emission Savings (tons)	Cost Savings ($)
10%	2020	8,247,375	4,885	2,123,938
40%	2022	17,869,313	10,585	9,127,063
80%	2025	129,208,875	76,535	40,641,125
Impacts are cumulative for all homes built and sold through the year indicated.				

Source: The Levy Partnership, Inc.

Comparison of Project Goals and Performance

The overarching goal of the research in this project was to develop new and innovative methods for building roof and wall systems that dramatically reduce energy use in factory built homes and take steps to transition the market in California to the new methods.

To achieve this goal, this research project followed an iterative process that focused on the design, testing and prototyping of advanced wall and roof assemblies of factory built homes. These advanced designs when compared with current building methods would represent a quantum leap in energy efficiency. During the design development phases, the impact of these advanced technologies was validated through energy simulation and cost calculations that demonstrate the significant energy savings, emission reductions and cost savings, thus accomplishing the overall goal of the research. Table 49 highlights the achievements of the research as compared with the initial objectives stipulated in the contract agreement.

Table 49: Agreement Objectives versus Research Accomplishments

	Agreement objectives	Research accomplishments
Technology features	• Develop an advanced wall design for factory use that uses continuous exterior insulation, such as structural composite panels. Continuous exterior insulation on walls proved the most attractive approach for meeting the new code. • Develop an advanced roof solution that is thermally more efficient than traditional roof construction with minimal impact on cost and labor. A more efficient thermal performance from the roofs would allow the manufacturers to trade-off with lower performance elsewhere.	• Developed an advanced wall assembly design with continuous exterior rigid foam insulation that improves the thermal performance of the wall system and results in a significantly tighter thermal envelope. • Developed an advanced roof assembly design with dense packed fiberglass insulation that increases the thermal performance of the roof overall. This solution improves the thermal performance at the roof eaves, where the depth is limited, thus addressing one of the weakest links in the building thermal envelope. • Developed and tested cool roof technologies. Analyzed the impact on cooling energy use in climates across California.
Cost effectiveness	• Have an annualized energy cost (total cost of ownership) markedly lower than current construction methods (i.e. monthly energy savings exceed monthly incremental loan costs) for homebuyers.	• Chapter 7 of this report discusses the total cost of ownership for a homebuyer, if the advanced technologies are implemented. While the initial first cost is estimated to be an average of $2671 per home, the monthly energy savings do exceed the monthly incremental mortgage in most cities, lending a net benefit of up to $11,502 for an occupancy period of 20 years. Thus the net benefit surpasses the initial cost in about 5 years.
Energy efficiency and demand impacts	• Reduce annual energy use per home by, on average, 1,510 kWh per year for cooling and fan use and 142 therms per year for heating when compared to current manufactured home construction. Energy savings will be based on both simulation and testing of full- scale prototype homes. • The technologies will reduce cooling equipment size, and associated load, by between ½- and 1-ton.	• Chapter 7 focuses on the annual energy use savings per home, obtained through energy simulation for 16 locations, one in each of the climate zones in California. Application of the advanced assemblies developed through this research is estimated to reduce the annual energy use for gas-heated homes up to 198 therms/yr and 1,804 kWh/yr. For electrically- heated homes, depending on location, savings ranges from 243 kWh/yr to 4,710 kWh/yr. (Note: these figures are not directly comparable to the average estimates initially provided. In part, this is due to the fact that the software used for the original analysis is unavailable and climate locations used for that simulation work were not options in the current simulation analysis.) The wide variation in results (indicative of the variation in California climates) suggest that where the home is placed profoundly impacts the value of the efficiency measures. There are areas where the technologies clearly and compellingly make economic sense, and others where, while saving energy, the measures are not cost-effective. • Two test units were built, instrumented with sensors and monitored to assess the performance of the advanced envelope solutions as compared to traditional construction. Results from these units were analyzed and evaluated. • The net savings of the advanced dense-packed roof solution with cool-roof and attic radiant barrier compared to the base case was estimated at $83/yr.
Carbon emissions	• The new technologies will reduce CO2e emissions by 1.31 metric tons per year per home.	• Chapter 7 discusses the impact of the advanced technologies on reducing the energy use of the buildings and consequently, carbon emissions significantly. The estimated reduction in CO_2 emissions is up to 2,891 lbs/yr. (1.3 metric tons).

Source: The Levy Partnership, Inc.

CHAPTER 8: Technology Transfer and Outreach

Technology Transfer Activities

As part of the culmination of this research work a significant outreach effort was required to transfer the results from this project to the manufactured housing market. A sequence of strategic tasks was planned with the purpose of disseminating this knowledge to the manufactured housing industry. This chapter describes these transfer activities, which include presentations, in-person correspondence, case studies, press releases, and a demonstration build. These descriptions include the purpose and nature of the outreach, topics to be covered within each outreach task, dates and locations (if applicable), and target audiences. The chapter also describes the outcome of each transfer activity.

This technology transfer plan outlines the activities intended to reach all parties within the manufactured housing industry. This includes manufacturers, retailers (who then pass on knowledge to home purchasers), community owners, suppliers (who may promote this technology through their own channels) and lenders. The intended audience of the outreach effort is indicated under each activity.

Approach

This task was approached using a number of strategic outreach techniques to distribute the knowledge and results gained from this research work. This section discusses activities undertaken by The Levi Partnership to transfer the advanced envelope technologies to the manufactured housing industry and other stakeholders. Technology transfer activities listed below provide a brief description of the activity, the parties involved, the audience, and the predicted impact. Timing of the activity, if applicable, is also indicated.

California Manufactured Housing Institute 2017 Annual Convention Presentation

- Target audience: Members of the California Manufactured Housing Institute (CMHI), including manufacturers, suppliers, and retailers across the state of California.
- Purpose: Disseminate the knowledge gained to the California manufactured housing industry at large.
- Date/Timeframe: March 15-16, 2017.

The CMHI 2017 Annual Convention was held in Rancho Mirage, California on March 15–16, 2017. The technical team, headed by Project Manager Emanuel Levy, presented and discussed the Advanced Envelope Research on Manufactured Homes. The 30-minute presentation focused on the project goals, approach, activities performed, results and advancements in thermal performance for the manufactured housing industry and is intended to disseminate the knowledge gained from the research project to the California manufactured housing industry at large.

The CMHI Annual Convention provided the technical team an opportunity to have one-on-one in-depth conversations with the attendees in support of this outreach effort.

Following the presentation the technical team was available at the conference to answer questions or provide additional information on the research project.

Advanced Envelope Systems Case Studies

- Target audience: Members of CMHI and the manufactured housing industry at large.
- Purpose: Summarize the developed schemes and present key findings from the advanced envelope technology research.
- Date/Timeframe: Circulated in print March 15-16, 2017, available online thereafter.

Three 2-page case studies were published by The Levy Partnership, as part of the dissemination and outreach effort for the research. Each case study focused on a technology developed as part of this research project: dense-packed roofs, cool roofs and attic radiant barriers, and stud walls with continuous exterior insulation.

These case studies included a brief description of the advanced envelope technology, its salient features and associated pros and cons, summary of key activities, and findings related to each technology developed as part of this research project. These case studies were distributed widely, mainly by email. Following the convention they were made available online.

Demonstration Build

- Target audience: California manufactured housing industry.
- Purpose: Demonstrate constructability of the advanced envelope designs as part of production line.
- Date/Timeframe: Week of March 6 or 20, 2017.

A full-scale prototype build was held at the manufacturing facilities of Golden West Homes in Perris, California. This demonstration build was conducted on a customer-occupied manufactured home that was upgraded to include all of the technologies developed within this research project. The build is intended to prove the efficacy of the combination of the developed wall and roof designs on the production line to the manufactured housing industry. Details of the build was provided to all the plant manufacturers within the state.

Press Release

- Target audience: Members of CMHI and Western Manufactured Housing Communities Association and the manufactured housing industry members and other stakeholders.
- Purpose: Publicize results of research project to manufactured housing industry.
- Date/Timeframe: Post demonstration build.

The technical team developed a press release was developed that was released over a number of distribution networks, including that of The Levi Partnership and those that may be provided by, CMHI, and WMA. This press release is intended to publicize the results of the research project to the manufactured housing industry and key stakeholders and focused on the research accomplishments and advancements in the manufactured home building process.

Results of Dissemination

California Manufactured Housing Institute 2017 Annual Convention Presentation

Emanuel Levy, representing The Levy Partnership, presented at the CMHI 2017 Annual Convention on March 16th, 2017. Topics within the 30-minute presentation commenced with introducing and discussing the impacts of the new HUD code on the manufactured housing industry. The presentation then focused on the findings from the Advanced Envelope Systems research and discussed the energy-efficient and cost-effective envelope solutions developed as part of this effort. Key items presented were the advanced wall and roof designs, whole house prototyping activities undertaken by The Levi Partnership, and the associated homeowner energy cost savings from these innovative technologies. Additionally, information on in-situ testing and other energy-saving technologies, namely ductless mini- split heat pumps, was covered during the presentation.

The presentation slides from the CMHI 2017 Annual Convention are included in Appendix F.

Advanced Envelope Systems Case Studies

Two 2-page case studies were developed by The Levy Partnership to be published as part of the dissemination and outreach effort for the research. The case studies focused on two topics: one on cool roof strategies, including reflective roof coverings and radiant barriers, and the second on the advanced wall and roof assemblies.

These case studies include brief descriptions of the technologies, discuss their salient features and associated pros and cons, summarize the key activities, and findings related to each technology developed as part of this research project. Also included were simulated annual energy bill reductions for the end-user.

These case studies were distributed online to all contacts within The Levy Partnership's database of interested parties, including manufacturers, retailers, community owners, suppliers, and lenders. Following this, they will be made available online via The Levy Partnership's website.

The two case studies are included in Appendix F.

Demonstration Build

A demonstration home build with the advanced wall and roof assemblies was conducted on March 21, 2017 at the manufacturing home facilities of Golden West Homes, Perris, California, which is a subsidiary of Clayton Manufactured Homes.

A brief report discussing the production process of the demonstration home that incorporated the advanced wall and roof technologies is included in Appendix F.

Press Release

The team developed case studies that will continue to be used to disseminate the research findings to the industry at large. These technical documents publicize the results of the project to the manufactured housing industry, thus serving the purpose of the planned press release.

Production Readiness Plan and Outreach

This section focuses on the production readiness and commercialization plans for the two developed Advanced Envelope technologies.

Full-scale production of the developed envelope assemblies will require modifications to the current, standard construction processes typically followed at the manufacturing plants. This section discusses the impact of the implementation of the advanced roof and wall technologies on the current manufacturing and production process. A production plan with steps that must be taken to incorporate these technologies in manufacturing plants is included in the following sections.

Description of Advanced Envelope Technologies

This research effort focuses on improving the energy performance of manufactured homes by changing the way the industry builds roofs and walls. Two envelope systems were designed that would provide cost-effective solutions for meeting the new stringent codes to the manufactured housing industry. These technologies are relatively simple and straightforward to incorporate into the production process. They were, in part, selected for this quality as changes to the production process are avoided by the plants with their potential to increase cost. The two advanced designs are described in the following sections.

Advanced Roof Design

The advanced roof design features dense-packed blown, fiberglass insulation at the eaves/sloped roof cavity (referred to as the compressed area) and standard density loose fill insulation in the center of the roof. Dense-packing blown fiberglass insulation is used strategically to increase the thermal performance of the roof in areas where depth is limited, that is at the roof eaves – traditionally one of the weakest links in the building thermal envelope. This is particularly the case with cathedral roof designs where the compressed area can run the entire width of the home. Because the insulation fills the full depth of the roof cavity at the eaves and typically several feet up the roof, baffles need to be provided in every roof bay to allow for free flow of ventilation air.

Advanced Wall Design

The advanced wall system incorporates a continuous layer of exterior insulation (expanded polystyrene or XPS) on the stud framing/wall sheathing. All edges are sealed by means of tape to create a continuous weather tight envelope. Continuous exterior insulation will increase the thermal performance of the wall system and result in a significantly tighter building envelope.

Most foam board products include tapes that assure weather tight construction obviating the need for an additional weather resistant barrier – a cost savings feature. As noted elsewhere, use of foam boards can necessitate special fasteners and, when used in thicknesses over 1”, special detailing to attach siding.

Impact of Advanced Envelope Technologies on the Current Production Process

This section discusses the impact of advanced envelope designs on the current production process at manufacturing plants. Production areas like inventory, equipment, facilities, productivity and other support systems will need to be reconciled in order for the new designs to be commercially viable. The following sections discuss the potential impacts of the designs on the current production process and propose strategies to address the potentially negative consequences associated with their implementation.

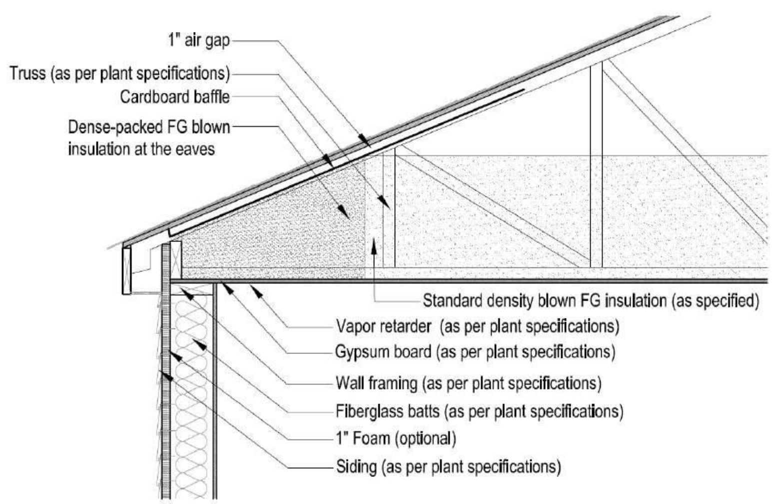
Advanced Roof

Impact on Plant Inventory

The advanced roof solution focuses on dense-packing blown insulation in the eaves of attic roofs and in the cavity of cathedral roofs. This design calls for the procurement of the following additional materials in the plant:

- Fiberglass insulation: Dense-packing the roof requires the use of blown fiberglass instead of cellulose (cellulose does not increase in R-value with increased density). Since this process increases the amount of insulation blown-in at the eaves, the number of bags of fiberglass insulation needed will be more than that needed to obtain a standard density of blown insulation.

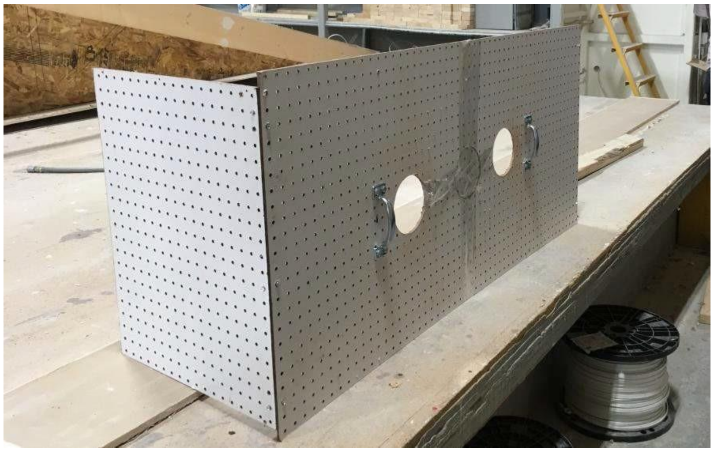
Figure 142: Cross-section of Advanced Roof Design



Source: The Levy Partnership, Inc.

- Dense-packing mold: The process of dense packing areas of the roof system requires a mold to be used at the truss bays to dense-pack the attic eaves. This mold is necessary to confine the area available to the blown insulation until the required density is achieved. The current design of the mold is made of pegboard and is designed to fit the geometry of the roof system. The holes in the pegboard allow air from the blowing process to escape while trapping the insulation in the cavity. Pegboard, standard nails and a handle would are needed to fabricate the mold. Simple instructions for construction of the mold are contained in the project documentation.

Figure 143: Dense-packing Mold



Source: The Levy Partnership, Inc.

- Baffles: In compliance with the HUD code the roof systems are required to provide a 1" ventilation air gap. In order to contain the dense-packed blown insulation and maintain the 1" airspace, a pathway for attic ventilation, baffles are required to be installed in the roof assembly.

Figure 144: Cardboard Baffles

Source: The Levy Partnership, Inc.

Figure 145: PVC Baffles

Source: The Levy Partnership, Inc.

Impact on productivity

- Increased labor hours: Manufacturing process analyses show that the number of workers and the time required for dense packing is more than what is required currently for standard practice. The additional labor hours needed to complete the dense packing process may cause a delay in the production line. It is expected that, over time, as the technology becomes standard practice for all homes at the plant, the production delays will likely reduce.[13] Use of the mold, described above, will help in minimizing the added production time associated with dense- packing.

Impact on equipment and tools

- Blowing machines: Manufacturing plants that currently use blown-in cellulose insulation for the roofs will need to configure their equipment to spray fiberglass instead of cellulose. This may include using different insulation-blowing machines or changing the equipment settings based on the properties of the insulation material. This would only slow production if the plant elects to use multiple insulation products that each require blower adjustment. Plants that use only fiberglass will see no impact on machine turnover.

- Mold: As detailed above, the mold is a new tool that is required to ensure that the target R- value and density is achieved during the dense packing of the roof. The design of the mold depends on several factors such as the truss spacing, the roof geometry and the target R-value to be achieved. It is likely that the plant will inventory several mold shapes and designs to accommodate various roof configurations. Over time, this tool is likely to

[13] Note that the dense-packing activities completed at the plants in this study did not contribute to delaying movement of the production line, even though they did increase labor hours.

evolve as the plant looks to minimize installation time and maximize quality (for example, consistent insulation density).

Figure 146: Dense-packing Using the Mold

Source: The Levy Partnership, Inc.

- Staples: The installation of baffles is an additional step to the current insulation process. It requires additional labor, and standard staples that are generally stocked at the manufacturing plants.

Advanced wall technology

Impact on plant inventory

The advanced wall solution focuses on incorporating a continuous layer of exterior insulation on the stud framing/wall sheathing. This design calls for the procurement of the following additional materials in the plant:

- Rigid foam boards and tapes: For the advanced wall design, studs walls will require continuous exterior rigid insulation foam boards (typically EPS or XPS) that need to be sourced for the construction of the advanced wall assembly. The size of the foam boards must be appropriate to the height of the home, usually 8’ or 9’ boards will be required. It is vital that the boards are compliant with HUD code, especially in terms of their compressive strength (in the absence of wall sheathing) and vapor perm rating. Polyethylene or polypropylene tapes must be used to seal the seams and edges of the foam boards to ensure it performs as a weather resistant barrier.

Figure 147: Exterior Rigid Foam Boards

Source: The Levy Partnership, Inc.

- Longer fasteners: The increased wall thickness due to the installation of rigid foam boards will require longer staples to penetrate the foam embed into the framing, and deeper jambs for the doors and windows. Further, the doors and windows may need additional blocking to provide for a flush outer edge.

Impact on productivity

- Increased labor hours: Manufacturing process analyses for the advanced wall technology show that the number of workers and the time required for adding continuous insulation to the walls is more than what is currently required for standard practice. The additional labor hours needed to complete the installation of foam boards may cause a delay in the production line. However, it is expected that, over time and with standardized practices, this impact will be largely minimized.

Impact on equipment and tools

- Longer router bits: The advanced wall assembly requires modifications to be made to the existing tools used by plant staff. The router bits used currently are not suitable for walls with additional exterior insulation. Longer router bits would be essential to penetrate through the additional layer of foam sheathing. It may be noted that the process of routing remains the same.[14]

- Stapling and nailing guns: Stapling guns that are compatible with longer fasteners and staples must also be procured for installation of the boards.

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[14] Note that the dense-packing activities completed at the plants in this study did not contribute to delaying movement of the production line, even though they did increase labor hours.

Production plan

To commercialize the advanced wall and roof technologies, manufacturing plants would need to undertake the following steps:

Step 1. Inventory needs

Roofs:

- Source blown fiberglass insulation with sufficient number of bags for dense packing. Dense- packing is designed to use standard fiberglass material to minimize the impact on inventory and product changeover.
- Baffles for ventilating attic roofs. The size and configuration of the baffles is based on the spacing of the truss bays and the area of dense packing. Generally smaller baffles (23”) are easier to install, especially in cases where the truss bays do not measure exactly 24” on center, (these situations would require manipulation of the baffle flaps). Baffles are available in several material options including cardboard and plastic. These products are routinely used and are familiar to the industry.
- Construct the dense-packing mold: The current mold design requires pegboards, nails, handles and supports.

Walls:

- Source foam boards: EPS or XPS foam insulation boards that meet the following requirements:
  - The size of the board is appropriate to the wall height
  - R-5 minimum
  - Perm rating > 1.0 (Class III)
  - 25 psi compressive strength min. in the absence of OSB sheathing
  - Meets ASTM D-1621: Compression Testing Of Rigid Cellular Plastics
  - Meets ASTM C-518: Standard Test Method for Steady-State Thermal Transmission Properties by Means of the Heat Flow Meter Apparatus
  - 75 or less flame spread
  - 450 or less smoke developed
- Obtain tapes for sealing edges and seams of foam boards.

Step 2. Code compliance and Design Approval Primary Inspection Agency approval

- Ensure that both assemblies meet the HUD code requirements and updated thermal standards in all climate zones of California. Initial review of both design concepts for code compliance have been satisfactory with minimum to no changes recommended.

- Obtain third-party Design Approval Primary Inspection Agency (DAPIA) approval and revise construction details, if applicable.

Step 3. Actions to be taken at the plant before production

Roofs

- Recalibrate the blowers for fiberglass insulation. For a more efficient production process it is best to completely shift to blown fiberglass from cellulose, to avoid constant changing and production line delays.
- Adjust the height of catwalks so that dense packing can be done without having to stand on the roof trusses, improving both the safety and productivity of workers.
- Fabricate the dense-packing mold based on the roof specifications and apply the following guidelines where feasible:
    - Ideally, the mold design should incorporate flexible or adaptable flanges to adapt to different truss bay widths, depths, and obstructions within the bay such as plumbing, electrical, mechanical. Make sure that the flanges prevent side blowouts.
    - Preferably, use a mold which covers multiple bays at a time reducing labor and increasing efficiency.
    - Add light frame superstructure or straps to minimize bending while lifting and moving the insulation mold.
- Assess if dense packing the roof at the roof build station on the floor level is easier and faster than from the scaffolding/catwalk at the roof level.
- Moving the insulation switch to the hose or providing a remote control switch, so that the control of the blower for dense-packing lies with the same worker who is blowing the insulation, will streamline the process and save labor and time. However, this will require redesign of the blowing machine and should be noted for future research.

Walls

- If possible, add a workstation for installing foam boards, so that it does not slow the line.

Step 4. Re-tooling and process changes

Walls:

- Procure longer fasteners, staples and compatible staple guns for installing the boards.
- Ensure that deeper jambs and frames for doors and windows are sourced to avoid the need for additional blocking.
- Use a router bit with a longer cutter to cut both, the rigid foam and the siding, in a single step saving time and labor.

Step 5. Plant staff training

Training may be required to familiarize staff with the following processes:

- Construction of the dense-packing molds for attic roofs
- Method of dense packing the eaves
- Installation of baffles (if applicable)
- Routing of openings and siding installation on thicker walls
- Taping of the foam boards at the edges and seams

Projected Cost Impact

The projected cost of implementing this production plan on a typical manufactured home is shown in Table 50.

Table 50: Additional Production Costs of Advanced Technologies

Additional production costs[a]	By 2020	By 2022	By 2025
Walls[b]			
Additional insulation cost	$609	$609	$609
Foam board fasteners cost	$7	$7	$7
Tapes cost	$62	$62	$62
Additional wall cost/home	$677	$677	$677
Roofs[c]			
Additional fiberglass insulation cost	$370	$370	$370
Baffles cost	$146	$146	$146
Additional roof cost/home	$516	$516	$516
Additional inventory costs/home	$1,193	$1,193	$1,193
Labor[d]			
Advanced wall assembly	$40	$30	$20
Advanced roof assembly	$45	$34	$23
Additional labor costs/home[e]	$85	$64	$43
Overall additional costs /home	**$1,278**	**$1,257**	**$1,235**

[a] Based on a home size – 48’ X 27’.

[b] Advanced wall insulation: R 13 FG batts + R 10 continuous insulation. Baseline wall insulation: R 11 FG batts.

[c] Advanced roof assembly: R 49 FG dense packed insulation in attic ceiling. Baseline roof assembly: R 19 blown FG attic ceiling.

[d] Based on a median labor wage of $14.45/hour (Source: United States Department of Labor).

[e] Based on the assumption that the additional labor hours would reduce (to 75% in each time period).

Source: The Levy Partnership, Inc.

The advanced wall assembly requires additional insulation, special fasteners and tapes which increase the production cost of the walls by about $677 per home. The advanced roof assembly requires more bags of insulation and other associated products, thus increasing the roof production costs by about $516 per home. The manufacturing process analysis shows that labor hours required to implement these technologies is more than the baseline process, thus adding to labor costs. However, it is expected that, over time, as the technologies are adopted widely and become standard practice, the impact on labor hours will reduce significantly.

CHAPTER 8: Accomplishing Project Goals

Progress Toward Achieving Goals

The Advanced Envelope Systems research project was initiated with a broad set of ambitious goals intended to lay the foundation for significant improvement in the energy efficiency of new manufactured homes. Four intertwined goals were described in the proposed effort: (1) involve a critical mass of California-based manufactured homebuilders as project partners; (2) identify, vet, develop, test, refine and demonstrate the best candidate technologies; demonstrate their potential energy savings benefits; and, (4) initiate the dissemination process with industry. The discussions that follow summarize progress made towards achieving each of these goals.

- Industry participation in the development and proof-of-concept process (the WHO): Having the industry partner in developing new technologies is a fundamental part of most successful research. End users must be vested in the results and recognize from the onset the impact of the new practices on their business. The Levi Partnership lead team involved key industry stakeholders in the development process to such a degree and in such a way that they share ownership of the results, a precondition for gaining widespread and immediate market acceptance. Their involvement and commitment to the results under pin the goal and expectation that the new construction methods pioneered by this project will be standard practice in California within five years of project completion. Industry participated at three levels:
    - A Technical Steering Committee (TSC) was formed consisting of engineers from the major homebuilding entities in the state. The TSC advised the project from inception through demonstration of the technologies.
    - The project team recruited a group of industry suppliers to provide advice on the use of their products; the group donated material and time as project cost share.
    - The wider industry audience, including the industry's trade organization, retailers and communities were kept abreast of developments and briefed on results. The involvement of retailers and communities, in particular, is key to eventual commercialization efforts as these entities are the direct conduit to customers that need to recognize the value of the advanced technologies. Together these organizations form the entire chain of businesses whose participation is required to bring the advanced technologies to market.
- Developing advanced technologies with commercial potential (the WHAT): The largest technical challenge faced by the team was identifying and developing new wall and roof component designs that achieve several goals, including: significantly reduce energy usage; are readily incorporated into the factory building environment; are cost effective;

and, add minimally to first cost. These goals were achieved by applying a combination of innovative design, concurrent engineering in the design-development process and leveraging the advantages afforded by factory production and rapid commercialization. These goals were achieved partly by leveraging the combined expertise of the technical team and that of the industry sponsors. The project produced solutions – advanced wall, advanced roof and cool roof technologies – that will significantly improve envelope performance and are tailored to the unique market conditions and wide range of climates found in California.

- Demonstrating potential energy benefits (the WHY): Compared to current construction methods, the new designs will lead to far less energy use with an estimated annual energy savings in a mixed fuel (electric and natural gas) home of 1,844 kWh and 104.6 therms, resulting in an average annual energy cost reduction of $467.[15]. For an all-electric home, annual energy savings will range from 243 to 4,710 kWh, resulting in an average annual cost reduction of $389. The new envelope technologies will enable cooling equipment downsizing of between ½ and 1 ton per home, equivalent to a non-diversified load reduction of 2.64 kW. The improvements will reduce per home CO_2e emissions by about 0.998 metric tons for a mixed fuel home and about 0.536 for an all-electric home. When these estimates are combined with Table 50, the estimated simple payback will be about 6 years.

Table 51: Average Measured Reductions of Annual Energy Use and Emissions

Energy and Related Benefits	Measured Impact (per home)	Measured Impact (per 1,000 homes)
Electric energy use reduction (kWh/home/year) for mixed fuel home*	1,844	1,844,000
Electric energy use reduction (kWh/home/year) for all electric home	243 -4,710	--
Natural gas consumption reduction for mixed fuel home (therms/home/year)*	104.6	104,600
Reduction in cooling equipment capacity (tons/home/year)	Between ½-1 tons	N/A
Carbon emissions reductions (metric tons/home/ year) for mixed fuel home*	0.861	861
Carbon emissions reductions for all electric home	--	--
*** Excluding locations where heating and cooling loads, and in turn the reductions are minimal (<500 kWh reduction, <35 therms reduction).**		

Source: The Levy Partnership, Inc.

[15] The United States Energy Information Administration tabulates the utility costs for California as of September 2016 as $1.29/therm and $0.18/kwh. These values are used to estimate the cost impacts.

Table 51 provides estimates of the energy, load and carbon emission reductions that will result from adoption of the advanced envelope technologies. The figures assume that the technologies are employed mainly in locations where they will have the greatest impact and therefore provide that highest cost benefit ratio. Rate of uptake in the technologies is difficult to predict but favor aggressive projections for several reasons, including: the number of new home sales in the state continue to increase, the majority of new homes are being sold in hot climates where cool roof technologies have the greatest impact, and the industry standards for energy performance are set to change within a year. To the latter point, the advanced technologies offer attractive options for manufacturers to meet the new standard and, indeed, the technologies were presented to DOE as evidence that the industry is capable of building energy efficient homes cost effectively.

- Commercial adoption of the advanced envelope technologies (the HOW): The final and ultimate measure of success is the pace of industry adoption of the new technologies. The process of commercialization and, specifically, assisting industry as they assess the value of the research products for their own markets and home designs and the process of folding the new designs into their manufacturing methods is underway. Dissemination steps included in the current work included the following:
    - Working directly with each of the home manufacturers on the team in building prototypes (both homes for testing and commercial sale.
    - Providing presentations to industry groups in the state.
    - Developing detailed design and product information needed to convey the new building methods to home manufacturers.
    - Assessing and resolving any potential code barriers.
    - Developing printed material to aid in information dissemination.

  Broad adoption of new technologies takes time and, as is the case with the advanced technologies that depend on market acceptance (as opposed to regulatory drivers) requires a market push from multiple directions. Ways in which the results of the current work can continue to gain traction, with broad adoption of advanced envelope technologies, are explored in the following discussion.

Next Steps

The project results demonstrated conclusively advanced technologies are cost effective, commercially-viable and offer new manufactured home buyers a compelling value proposition: pay a bit more for the home but enjoy lower monthly homeownership costs. However, the major hurdle to the advanced technologies is first cost, albeit this is partly a perceived notion for most buyers. The reality is that manufactured housing is perhaps the most first-cost sensitive housing option in the state and small increases in home cost – like those associated with the measures developed through this work – are resisted by lenders, retailers and customers.

Lenders rarely recognize in their lending terms that improved energy performance is not an amenity but rather a method for improving value while lower homeownership costs making for a safer loan. Retailers are rarely equipped to promote the value proposition and buyers don't fully recognize that somewhat counterintuitive idea that a slightly higher sticker price translates into lower ownership costs. Gaining market share for the technologies, therefore, will require overcoming at least some of these barriers and is likely to require additional market drivers such as the following:

- Pairing envelope technologies with advances in HVAC design: The research focused on the building envelope making important strides in improving efficiency. The potential for leveraging those savings by pairing the envelope improvements with high performance mechanical equipment will complete the process, magnify the energy benefits and provide the basis for reaching zero net energy use. should consider sponsoring research to develop a fully integrated energy solution for manufactured housing using the results of this work as part of the solution. Ironically, given its intrinsic appeal, it may be easier to commercialize a net zero home than just the thermal improvements developed through this effort.
- Creating market drivers such as rebates, tax credits, sustained promotion directly to customers: The affordable nature of manufactured homes, the fact that it is the only and, arguably in many instances, the best option for families living on modest incomes, means that first cost is paramount. In some cases, households are not able to qualify for a small increase in loan amount associated with the advanced envelope features. More commonly, to be able to purchase the measures necessitates trading off other basic features, like an additional bedroom, and so on. While this is an artifact of the lending process (as noted, lenders don't' consider the energy savings benefits in setting loan terms) it is a market reality. In response, and recognizing the importance of energy costs in overall home affordability, the state or other agencies with a vested interest in promoting efficiency (utilities) should consider ways to subsidize the advanced envelope technologies, such as, rebates to manufacturers, loan guarantees and a robust and sustained promotion program targeting retailers and consumers. Given the relatively small number of home manufacturers in the state, a targeted promotion/incentive program is likely to an immediate and profound impact on construction and buying practices.
- Changes in building standards: Generally, measures that are shown to be cost-effective and commercially-available find their way into building standards, codification being easier route than market acceptance. However, with manufactured housing, regulation is a less dependable course. The last time the manufactured housing standards were updated was in 1994 (the standards are promulgated by HUD and are nationally preemptive). Partly on the strength of this work for, The Levi Partnership team was instrumental in developed new energy standards for manufactured housing through the

ASRAC process facilitated by the United States Department of Energy. The new standard, when enforced, will require industry to look to technologies like advanced envelope measures, to comply. Demonstrating that meeting tougher energy standards are within reach was one of the major accomplishments of this work. When the standards are released, the manufacturers in the state will be positioned to seamlessly adopt the measures that they have already demonstrated.

LIST OF ACRONYMS

Term	Definition
ACH	Air changes per hour
AFUE	Annual fuel utilization efficiency
ANSI	American National Standards Institute
ASCE	American Society of Civil Engineers
ASRAC	Appliance Standards and Rulemaking Federal Advisory Committee
ASTM	American Society for Testing and Materials International
BIBS	Blown-in blanket system
Btu	British thermal units
CI	Continuous insulation
CMHI	California Manufactured Housing Institute
CO_2e	Carbon dioxide-equivalent
CZ	Climate zone
EER	Energy efficiency ratio
EPS	Expanded polystyrene
FG	Fiberglass
HD	High-density, when referring to insulation
HUD	United States Department of Housing and Urban Development
HVAC	Heating, ventilation, and air conditioning
IECC	International Energy Conservation Code
IRC	International Residential Code
Kw	Kilowatt
kWh	Kilowatt hours
OSB	Oriented strand board
OEM	Original equipment manufacturer
Plf	Pounds per linear foot

Term	Definition
RBS	Radiant barrier system
RH	Relative humidity
SBRA	Systems Building Research Alliance
SEER	Seasonal energy efficiency ratio
SIS	Structurally insulated sheathing
Therm	100,000 Btu
TMY	Typical meteorological year
TSC	Technical Steering Committee
TVA	Tennessee Valley Authority
VR	Vapor retarder
WRB	Weather-resistant barrier
XPS	Extruded polystyrene

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Appendix A: Code Compliance Reports and Research: Walls and Roofs

RESOURCES
APPLICATIONS,
DESIGNS &
CONTROLS, INC.

3220 E.59TH STREET
LONG BEACH, CA 90805
Tel (562) 272-7231
Fax (562) 529-7513
www.RADCOinc.com
Email: info@RADCOinc.com

September 16, 2013

Mr. Emanuel Levy, RA The Levy Partnership
1776 Broadway, Suite 2205 New York, NY
10019

Re: Advanced Envelope Research for Manufactured Housing

Based on your request, RADCO has performed this research to identify the necessary requirements or testing needed to qualify the material XPS insulation (Foamular), for use in the wall construction of manufactured home, under the Manufactured Home Construction and Safety Standards.

Based on the data and details provided to RADCO and on the HUD Interpretative Bulletin C-5-76, we found that the XPS insulation Foamular material can be used in exterior wall construction of manufactured homes if it meets the following criteria:

1- The Extruded expanded polystyrene foam plastic material is **not to exceed 1" in thickness**, it can be used in the cavity of walls or ceilings as sheathing or backer board for exterior coverings when it meets the following conditions:

(i) The sheathing shall have a minimum compression strength of 25 psi when tested as per ASTM-D 1621-64 and an average thermal conductivity (k factor) of 0.20 BTU-in/hr ft 5 degree F at 75 degree F mean when tested as per ASTM-C-518-70

(ii) A minimum of two inches of mineral fiber insulation is provided within the wall cavity and a minimum of four inches of mineral fiber insulation is provided in the ceiling cavity (in ceiling application).

(iii) An interior finish material is provided on exterior wall and ceiling surfaces with equivalent fire resistive properties to 5/16" gypsum board.

(iv) A wall framing system consisting of 2" X 4" studs at 16" o.c. or equivalent when the sheathing is installed within the wall cavity.

(v) (For ceiling application), A roof framing system consisting of roof trusses or equivalent framing members installed at a min. spacing of 16" o.c.

(vi) The sheathing shall not be placed in contact with heat sources such as chimneys, heater vents or other surfaces which provide long term exposure to temperatures above 150 degree F. Clearance from the sheathing to the heat source shall be provided in accordance with NFPA 89M, heat producing appliance clearances.

(vii) A vapor barrier is provided on the warm side of the wall and ceiling cavity in accordance with Subpart F of the Manufactured Home Construction and Safety Standards.

(viii) The sheathing is installed in accordance with the manufacturer's installation instructions, including the provision for controlling joint locations by either the use of tongue and groove sheathing or by placement of joints over structural framing members.

In addition to all of the above requirements, the following is also needed in general:

1- The XPS insulation (Foamular) should have a flame spread rating of 75 or less and a smoke- developed rating of 450 or less (not including outer covering of sheathing).
2- If the XPS insulation (Foamular) and siding are used to replace structural sheathing required for transportation, a transportation test needs to be done to prove the integrity of the wall construction during transportation. However, if the home in question is approved to be built w/o structural sheathing no transportation test should be required unless other elements of the design has changed.
3- The design is only to be used in wind zone 1.
4- The fastening of the XPS insulation (Foamular) material to the framing members is to follow the
5- manufacturer's installation instructions.
6- Also the fastening of the siding material to the framing members need to be identified (it has to be
7- per the manufacturer's installation instructions).
8- Heat loss calculation hves to be prepared for the envelope to meet the Manufactured Home Construction and Safety Standards.
9- If the construction is intended for WZ 2 & 3, each of the manufactured home wind resisting parts including but not limited to shear walls and their fastening and anchoring systems, cladding materials such as siding, exterior sheathing, wall studs, exterior glazing and their connections and fasteners have to be designed by a professional engineer or architect to resist (A) The design wind loads for Exposure C specified in ANSI/ASCE 7-88, "Minimum Design Loads for Buildings and Other Structures," for a fifty-year recurrence interval, and a design wind speed of 100 mph, as specified for Wind Zone II, or 110 mph, as specified for Wind Zone III (Basic Wind Zone Map); or (B) The wind pressures specified in the table provided in the Manufactured Home Construction and Safety Standards.

If the Extruded expanded polystyrene foam plastic material exceeds 1" in thickness, then:

The foam plastic insulating material has to be tested as required for its location in wall and/or ceiling cavities in accordance with testing procedures described in the Illinois Institute of Technology Research Institute Report, "Development of Mobile Home Fire Test Methods to Judge the Fire-Safe Performance of Foam Plastic Sheathing and Cavity Insulation, IITRI Fire and Safety Research Project J- 6461, 1979" or other full-scale fire tests accepted by HUD, and it is installed in a manner consistent with the way the material was installed in the foam plastic test module. The materials must be capable of meeting the following acceptance criteria required for their location:

(i) Wall assemblies. The foam plastic system shall demonstrate equivalent or superior performance to the control module as determined by:

(A) Time to reach flashover (600 °C in the upper part of the room);

(B) Time to reach an oxygen (O_2) level of 14% (rate of O_2 depletion), a carbon monoxide (CO) level of 1%, a carbon dioxide (CO_2) level of 6%, and a smoke level of 0.26 optical density/meter measured at 5 feet high in the doorway; and

(C) Rate of change concentration for O_2 , CO, CO_2 and smoke measured 3 inches below the top of the doorway.

(ii) Ceiling assemblies. A minimum of three valid tests of the foam plastic system and one valid test of the control module shall be evaluated to determine if the foam plastic system demonstrates equivalent or superior performance to the control module. Individual factors to be evaluated include intensity of cavity fire (temperature-time) and post-test damage.

(iii) Post-test damage assessment for wall and ceiling assemblies. The overall performance of each total system shall also be evaluated in determining the acceptability of a particular foam plastic insulating material.

(b) All foam plastic thermal insulating materials used in manufactured housing shall have a flame spread rating of 75 or less (not including outer covering or sheathing) and a maximum smoke-developed rating of 450.

This concludes our research. Should you have any questions, please do not hesitate to contact the undersigned.

Sincerely

R A D C O

Michael L. Zieman,
P.E. President

Hala Jawad

Director Plan Review Services

Final Code Compliance Report on Advanced Roof Designs

Ten alternative roof system designs for factory built homes were developed based on the specifications submitted earlier in the project. Summaries on all the developed designs were submitted to two leading third party agencies for review and approval under the codes and standards that regulate the construction of factory built homes. The summaries included a discussion of the advantages and challenges posed by each and construction details of connections to attached building components (see deliverable 2.2.3 for details).

The following two sections include brief reports on the review by the third party agencies, which discuss their assessment of hurdles to using the designs under the HUD code. The discussion also includes likely issues to be encountered including thermal performance, propensity for condensation and durability etc.

1 RADCO, Inc.

Review by Mike Zieman, President

General comments –

- Specify 3/8” thickness for gypsum board on all sketches
- Need to discuss shingle attachment and surface temperature issues with foam insulation under the sheathing. Contact shingle manufacturers, although this shouldn’t be an issue since it’s done in the site building arena.

Design 1 –

- The baffle profile shown in the cross-section sketch may not comply with the strict wording of the code. But there are plants known that use the Accuvent product currently.
- Need to ensure that the required density is achieved in the dense-packed region.

Design 2 –

- Discussion regarding the limitation that batts don’t insulate well between chords. Trying to insulate with full-size batts may resolve the issue (that is, actual 16” batts in nominal 16” cavity).

Design 3A –

- Eliminate. Provides no advantage over 3B but will be more difficult to construct and probably cost more.

Design 3B –

- Remove current note on vapor retarder. Add note specifying that rigid insulation must have perm rating Class III or higher.
- Show Class I or II vapor retarder on the ceiling side.

Design 4A –

- Eliminate. Provides no advantage over 4B but will be more difficult to construct and probably cost more.

Design 4B –

- Remove current note on vapor retarder. Add note specifying that rigid insulation must have perm rating Class III or higher.
- Show Class I or II vapor retarder on the ceiling side.

Designs 3AX/4AX –

- Eliminate. Provides no advantage over 3BX/4BX but will be more difficult to construct and probably cost more.
- Modify the reduced framing designs to include 2x6 rafters instead of 2x4.
  (I do have a concern *however with the 2X4 which must span the width of the home (12, 14 or 16 feet). Notwithstanding that it calculates to carry the weight of the gyp and insulation I am concerned about any warping/bending that would telegraph through and make the ceiling appear wavy. In my experience it only takes a 1/8" or so deflection to give a wavy appearance to the ceiling. Consumers do not like wavy ceilings.)*

Designs 3BX/4BX –

- Show Class I or II vapor retarder on the ceiling side.
- Issue regarding the HUD code compliance of the unvented designs – When 504(c)(3) speaks of "closed cell type construction" it is not referring to insulation which is closed cell. Rather it is referring to the space ("cell" if you will) created by the "parallel membrane roof section”. The "cell" in 3BX/4BX is the space where the HD batt/ blown insulation is located. The cell is "closed" because it is not ventilated and is enclosed on all sides. The wording in 504(c)(3) is ancient and confusing but I have always taken it as explained above and believe it was originally written to allow a sold rafter roof, such as is shown in 3BX/4BX, to be built without having to be ventilated.
- Modify the reduced framing designs to include 2x6 rafters instead of 2x4.
  (I do have a concern however with the 2X4 which *must span the width of the home (12, 14 or 16 feet). Notwithstanding that it calculates* to *carry the weight of the gyp and insulation I am concerned about any warping/bending that would telegraph through and make the ceiling appear wavy. In my experience it only takes a 1/8" or so deflection to give a wavy appearance to the ceiling. Consumers do not like wavy ceilings.)*

2 NTA, Inc.

Review by Eric Tompos, Vice-president of Compliance, and Doug Mills, Director of DAPIA Services

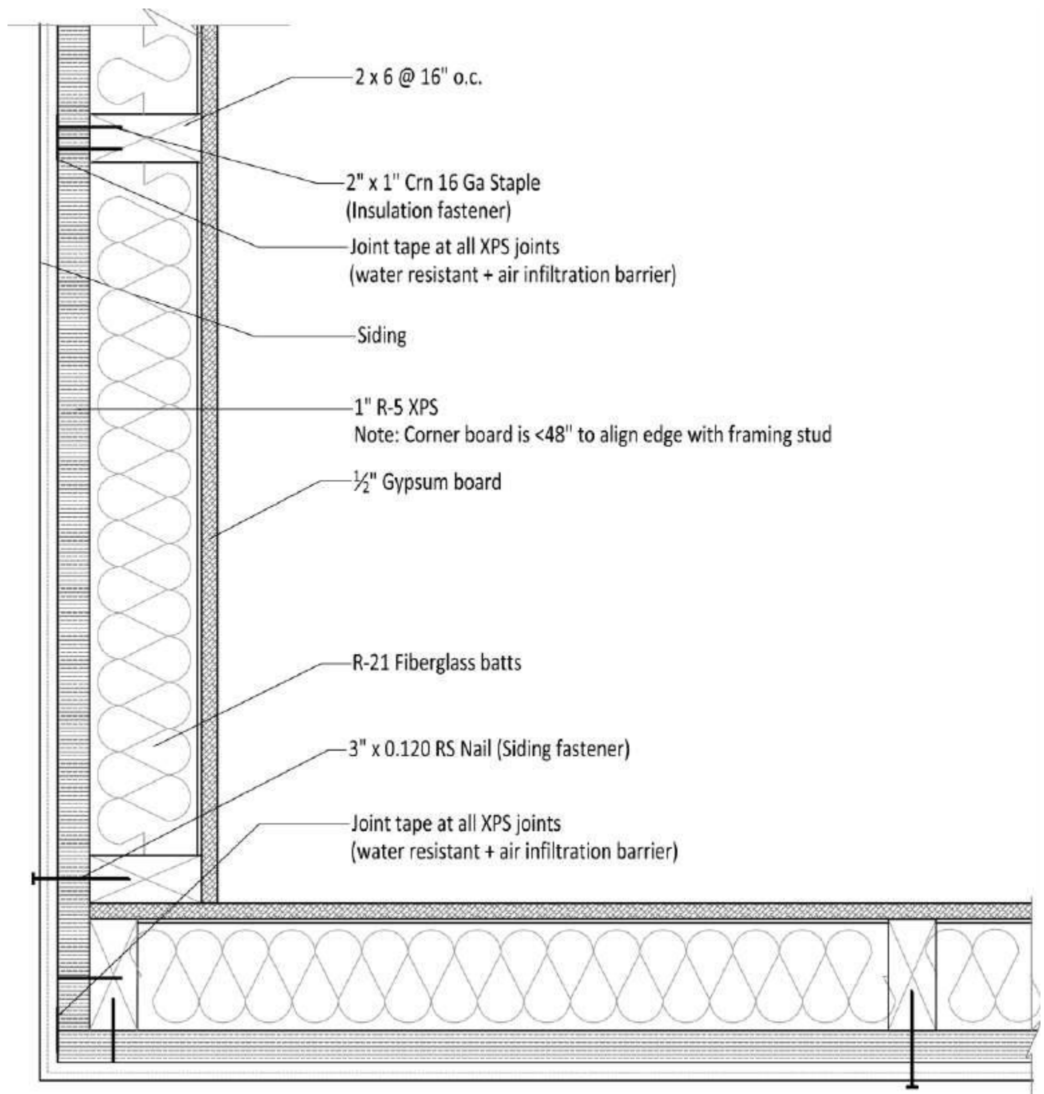
NTA's review focused primarily on compliance issues with the unvented solutions. Following a detailed discussion on HUD code section 3280.504(c)(3) regarding parallel membrane roof systems, NTA is of the opinion that an AC letter (section 3280.10 Use of alternative construction) would be required seeking code approval for the unvented solutions. To further confirm this, Doug Mills will reach out to HUD directly to get their interpretation of the cited sections and clarify their position on unventilated HUD roof cavities.

Appendix B: Prototyping Process: Walls and Cathedral Roofs

Typical Construction Details of Advanced Walls and Roofs

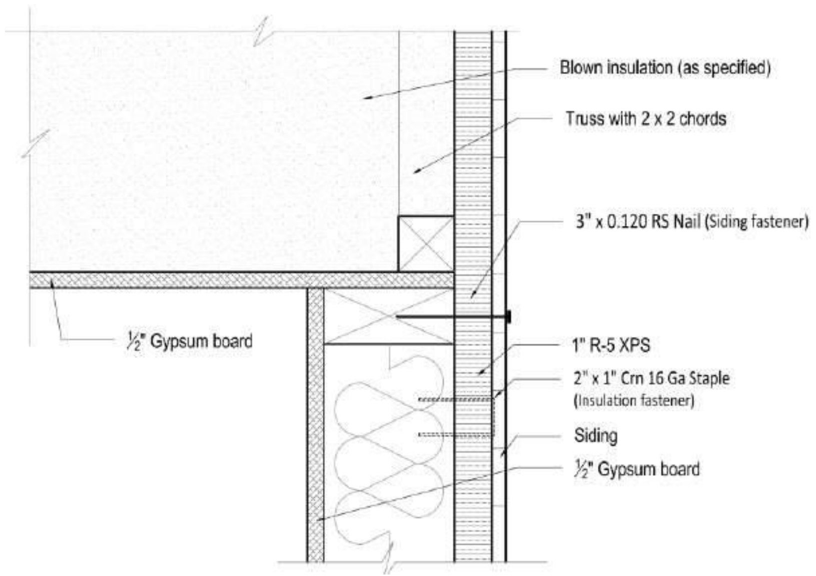
Figure B-1through Figure B-3 shows construction details and how the exterior continuous insulation is incorporated into the wall assembly.

Figure B-1: Plan View of Wall Detail



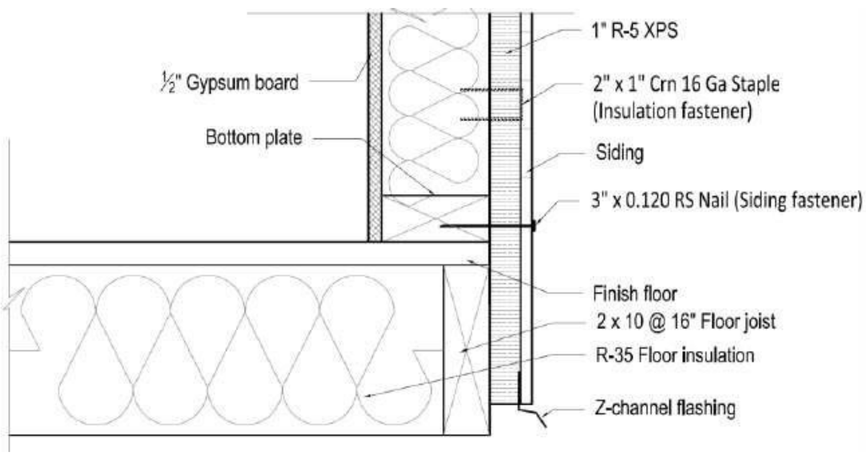
Source: The Levi Partnership, Inc.

Figure B-2: Detail at Top Plate (gable wall section)



Source: The Levi Partnership, Inc.

Figure B-3: Detail at Bottom Plate



Source: The Levi Partnership, Inc.

Dense-pack Ceiling Insulation Protocol

Figure B-4 through Figure B-8 show images from prior builds demonstrating the standard protocol for dense-packing blown insulation into roof attic eaves. Click here (link) to watch a short video on dense-packing a roof bay.

Figure B-4: Mold used to Dense-pack at Eave (sized to fit truss bay)

Source: The Levi Partnership, Inc.

Figure B-5: Mold Placed at Roof Eave before Blowing in Insulation

Source: The Levi Partnership, Inc.

Figure B-6: Dense-packing Mold Placed at Roof Eave

Source: The Levi Partnership, Inc.

Figure B-7: Blowing in Eave Insulation to the Required Density within the Mold Cavity

Source: The Levi Partnership, Inc.

Figure B-8: Dense-pack Insulation at the Eave (after removing mold from the truss bay)

Source: The Levi Partnership, Inc.

Exterior Continuous Insulation on Walls

Figure B-9 through Figure B-15 are images from prior builds focusing on installation of continuous foam insulation on exterior walls.

Figure B-9: Foam Boards Lined up against the Wall

Source: The Levi Partnership, Inc.

Figure B-10: Foam Boards being Set, Stapled and Taped

Source: The Levi Partnership, Inc.

Figure B-11: Taping the Seams and Edges with Foam SealR Tape

Source: The Levi Partnership, Inc.

Figure B-12: Routing Out Wall Opening

Source: The Levi Partnership, Inc.

Figure B-13: Installing Siding on the Foam Board

Source: The Levi Partnership, Inc.

Figure B-14: Routing Wall Opening on the Siding

Source: The Levi Partnership, Inc.

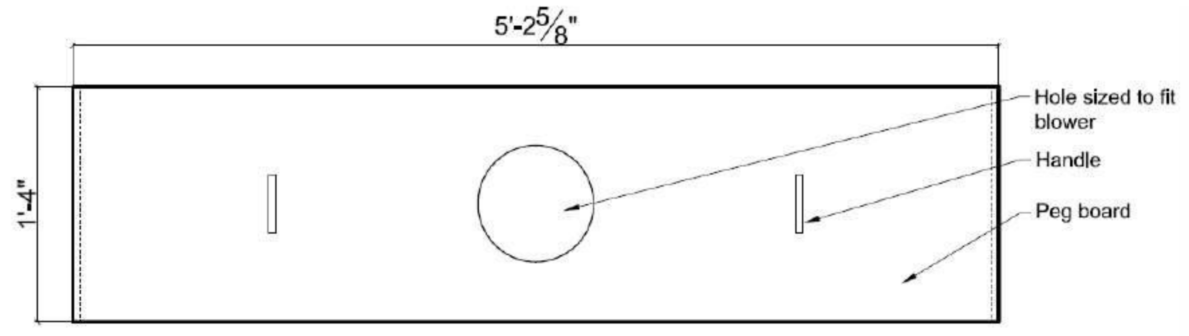
Figure B-15: Foam and Siding Installation at Gable End

Source: The Levi Partnership, Inc.

Dense-packer Build Drawings

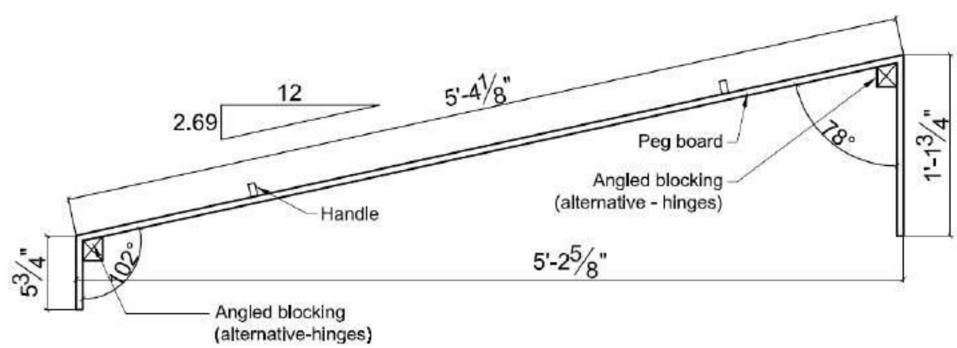
Figure B-16 through Figure B-19 show construction details for fabrication of the dense-packing mold used to install insulation at the eave end and the middle section (Mold-A).

Figure B-16: Mold A - Top View



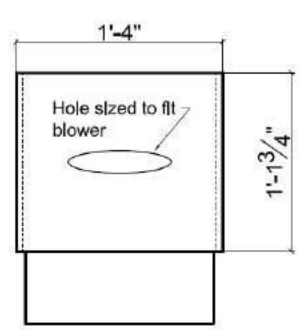
Source: The Levi Partnership, Inc.

Figure B-17: Mold A - Side View



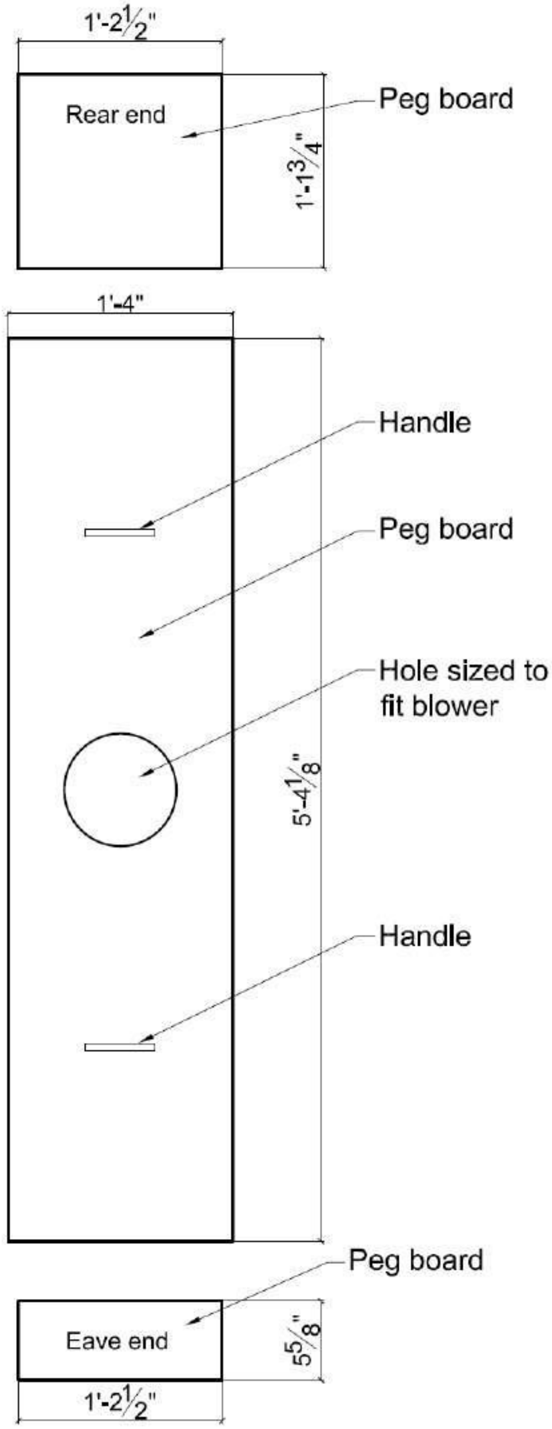
Source: The Levi Partnership, Inc.

Figure B-18: Mold A - Front View



Source: The Levi Partnership, Inc.

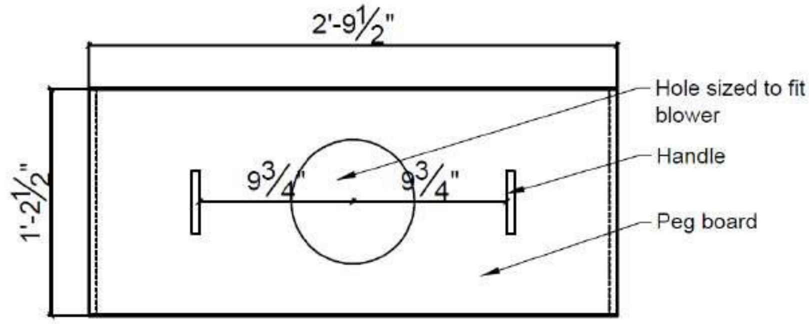
Figure B-19: Mold A - Surface Area Development



Source: The Levi Partnership, Inc.

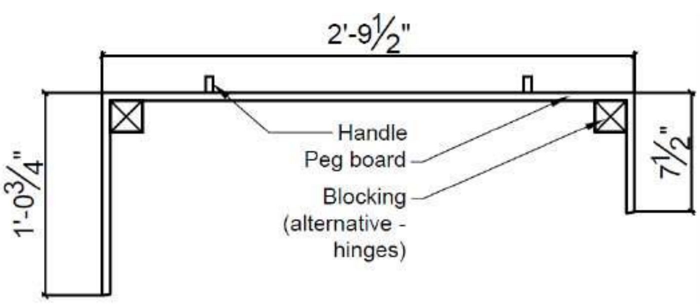
Figure B-20 through Figure B-23 show construction details for fabrication of the dense-packing mold used to install insulation at the ridge (Mold – B).

Figure B-20: Mold B - Top View



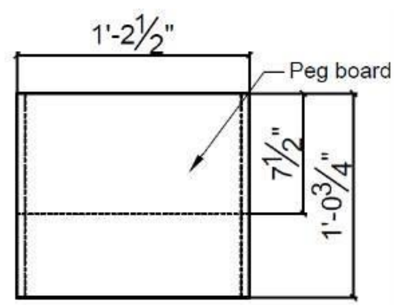
Source: The Levi Partnership, Inc.

Figure B-21: Mold B - Front View



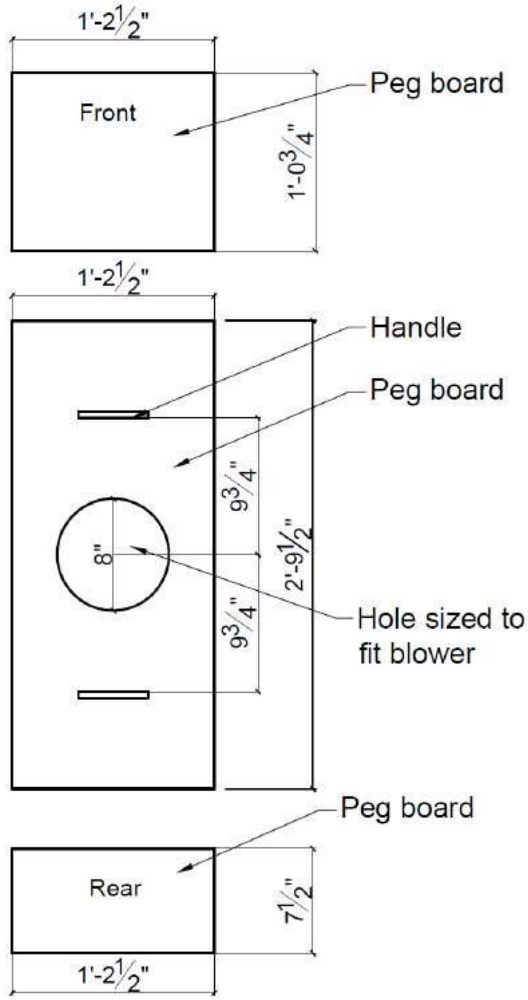
Source: The Levi Partnership, Inc.

Figure B-22: Mold B - Side View



Source: The Levi Partnership, Inc.

Figure B-23: Mold B - Surface Area Development



Source: The Levi Partnership, Inc.

Appendix C: Wall Laboratory Testing Equipment and Material Needs

This appendix section provides details on the equipment and material needs for the testing and demonstration.

Fasteners and Associated Tools

Fasteners and associated tools required for the meeting are listed in Table C-1 and Table C-2.

Table C-1: Fasteners and Associated Tools (Senco Products)

Code	Fasteners Standard	Description	Quantity	Thousands	Finish
A	Q25BAB	2½ in. × 7/16 Crn 15 Ga Staple	2 carton	10/m	Galv
B	P21BAB	2 in. × 1 in. Crn 16 Ga Staple	2 carton	10/m	Galv
C	G621ASBX	2 in. × 0.113 RS Nail	2 carton	5/m	Hot dip galv
D	H627ASBX	3 in. × 0.120 RS Nail	2 carton	5/m	Hot dip galv
E	K528ASBX	3¼ in. × 0.131 Coated Nail	2 carton	5/m	Hot dip galv
F	K529APBX	3½ in. × 0.131 Coated Nail	2 carton	5/m	Bright
G	KC31	4 in. Nail	–	–	–
Code	**Screws**	**Description**	**Quantity**	**Thousands**	**Finish**
H	08F300Y	3 in. × # 8 Wood Screw	2 tubs	1.6/m	Yellow Zinc
Code	**Special Product**	**Description**	**Quantity**	**–**	**Finish**
I	SQSSXP	3.5 90MM Europe	1		
J	WC130SP	4½ in. wide crn Europe	1		
K	S28BAB	3 in. × 1/2 in. Crn Staple Europe	3 carton		Galv
L	S29BAB	3½ in. × ½ in. Crn Staple Europe	3 carton		Galv
M	SP30BAB	4 in. × 1 in. Crn Staple Europe	4 carton		Galv
N	SP29BAB	3½ in. × 1 in. Crn Staple Europe	4 carton		Galv
	Tool Identifier	**Description**	**Quantity**	**–**	**–**
	4Y0001N	WC200 XP WC Stapler	2		
	5B0001N	SN951XP Framing Nailer	2		
	660101N	SQS55 Stapler	2		
	6Y00011N	DS340A/C Screwdriver	1		
	2P0001N	DS275-18V Cordless Screwdriver	1		

Source: The Levi Partnership, Inc.

The following screws were used to attach 2 × 4 (nominal) furring over 2 in. of Styrofoam with 2 in. embedment into the studs. Screws require Spider drive bits.

Table C-2: Fasteners and Associated Tools (FastenMaster products)

Code	Screws	Description	Quantity	Pieces	Finish
O	HeadLOK	5½ in. min	1 box	50	

Source: The Levi Partnership, Inc.

Insulation and Associated Products

Styrofoam tests (Supplier: DOW)

- 1 – Pallet or unit of 4 ftx9 ftx1 in. Dow Styrofoam sheathing panels 96 pcs.
- 1 – Pallet or unit of 4 ftx9 ftx2 in. Dow Styrofoam sheathing panels 48 pcs.
- 1 – Froth Pak 220 (insulation not sealant) kit, with hose and nozzles
- 1 – Case of Great Stuff Gaps and Cracks Pro
- 1 – Case of Great Stuff Adhesive
- 1 – Case of Great Stuff Window and Door Pro
- 2 – Pro 14 Great Stuff Dispensers (guns)
- 1 – Case of Great Stuff gun cleaner
- 1 – Case Weathermate Construction Tape 2.875 in. wide
- 1 – Case Weathermate Construction Tape 1.875 in. wide
- 1 – Case of Weathermate Straight Flashing 4 in. × 100 ft
- 1 – Case of Weathermate Straight Flashing 6 in. × 100 ft
- 1 – Box Weathermate Flexible Flashing 6 in.
- 1 – Box Weathermate Flexible Flashing 9 in.
- 1 – Box Weathermate window sill pans

Foam-Control Nailbrace tests (Supplier: AFM Corp.)

- 6 pieces – 1.625 in. × 4 ft.× 8 ft, Foam Control Nailbrace panels
- 8 pieces – 1.625 in. × 4 ft.× 9 ft, Foam Control Nailbrace panels
- 4 pieces – 2.875 in. × 4 ft.× 9 ft, Foam Control Nailbrace panels
- 6 rolls edge sealing tape

Siding

LP SmartSide siding (Supplier: LP Corp.)

- 18 each – ⅜in. 4 ft.× 8 ft.8 in. o/c SmartSide Panel Siding
- 18 each – 7/16 in. 4 ft.× 8 ft.8 in. o/c SmartSide Panel Siding

Cempanel (Supplier: Cavco)

- 10 sheets – 4 ft.× 8 ft.each

Vinyl (Supplier: BlueLinx Corp.)

- 32 squares – D5 Dutch Lap Parkside #115 Pearl
- 50 pieces – Sturdy Vinyl Starter Strip #303

- 40 pieces – ⅝in. J-Channel Pearl #36585
- 10 pieces – 3 in. Outside Corner Post Pearl #40022
- 10 pieces – 4 in. Outside Corner Post Pearl #40020

Window Framing

Metal L-clips (Supplier: AFM Corp.)

- 10 pieces – 4 ft.long R-5 L-clips
- 4 pieces – R-10 L-clips

Other Wall Build Materials

(Supplier: Cavco) (quantities as required)

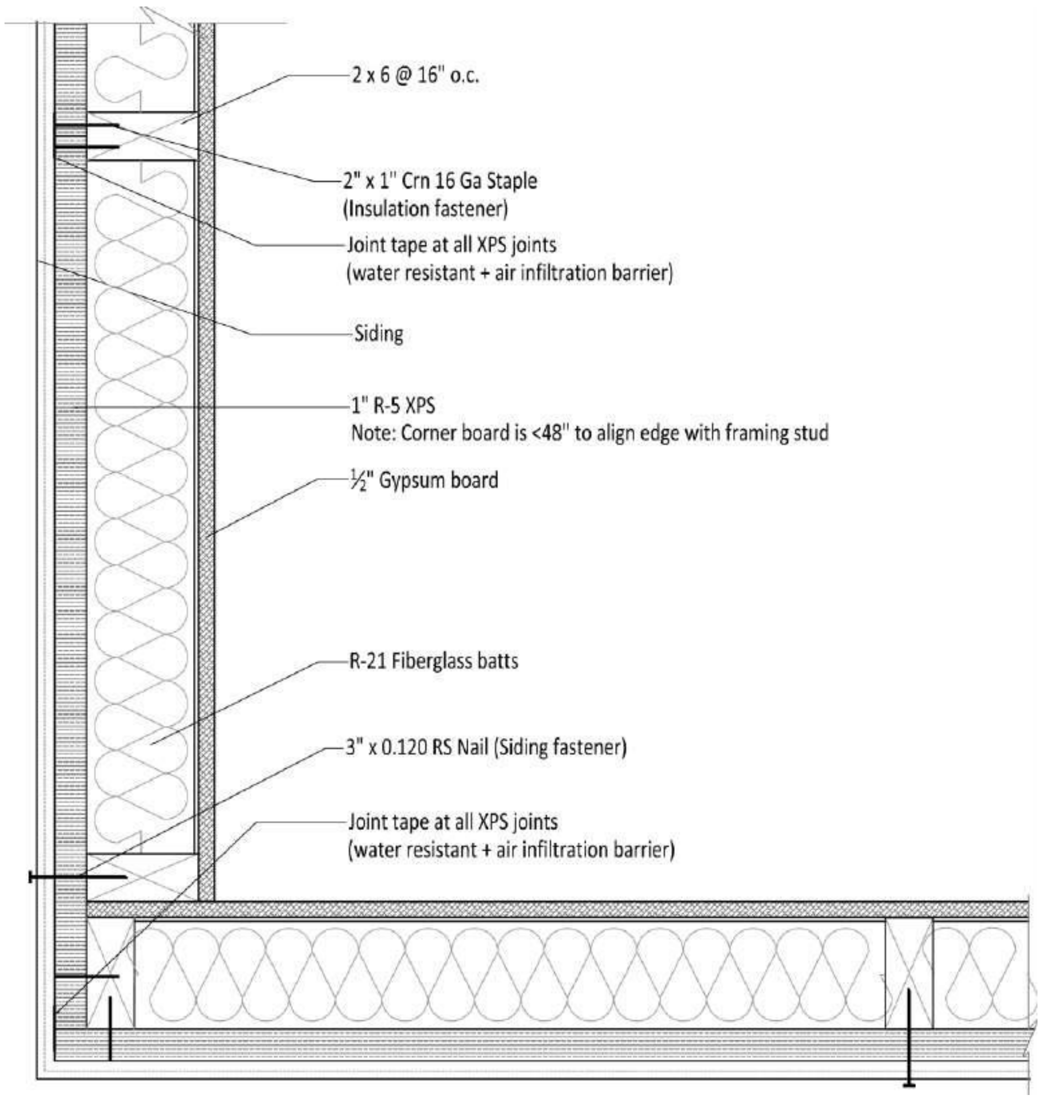
- Framing
- Gypsum board
- OSB
- Doors
- Windows and doors
- Flashing
- Weather resistant barrier
- Materials for partial floor and roof

Appendix D: Roof Laboratory Testing, Phase 1 – Details

Exterior Rigid Wall Insulation Protocol

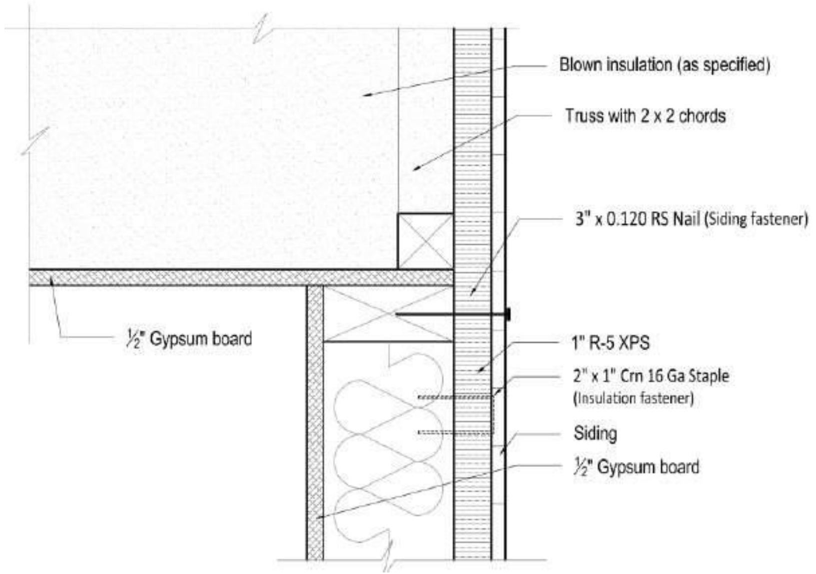
Below are construction details showing how the exterior continuous insulation is incorporated into the wall assembly.

Figure D-1: Plan View of Wall Detail



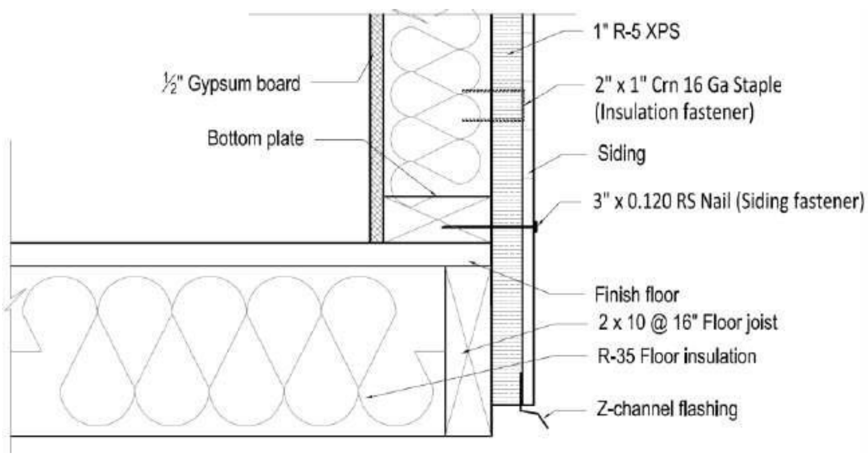
Source: The Levi Partnership, Inc.

Figure D-2: Detail at Top Plate (gable wall section)



Source: The Levi Partnership, Inc.

Figure D-3: Detail at Bottom Plate



Source: The Levi Partnership, Inc.

Dense-pack Ceiling Insulation Protocol

Figure D-4 through Figure D-8 demonstrate the protocol for dense-packing blown insulation into roof attic eaves.

Figure D-4: Mold used to Dense-pack at Eave (sized to fit a truss bay)

Source: The Levi Partnership, Inc.

Figure D-5: Mold Placed at Roof Eave before Blowing in Insulation

Source: The Levi Partnership, Inc.

Figure D-6: Dense-packing Mold Placed at Roof Eave

Source: The Levi Partnership, Inc.

Figure D-7: Blowing in Eave Insulation to the Required Density within the Mold Cavity

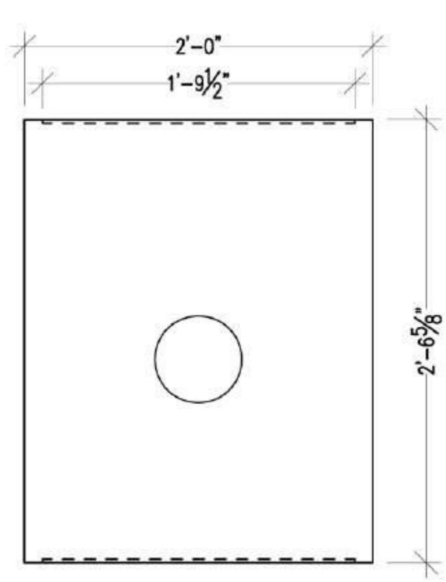
Source: The Levi Partnership, Inc.

Figure D-8: Dense-pack Insulation at Eave (after removing mold from the truss bay)

Source: The Levi Partnership, Inc.

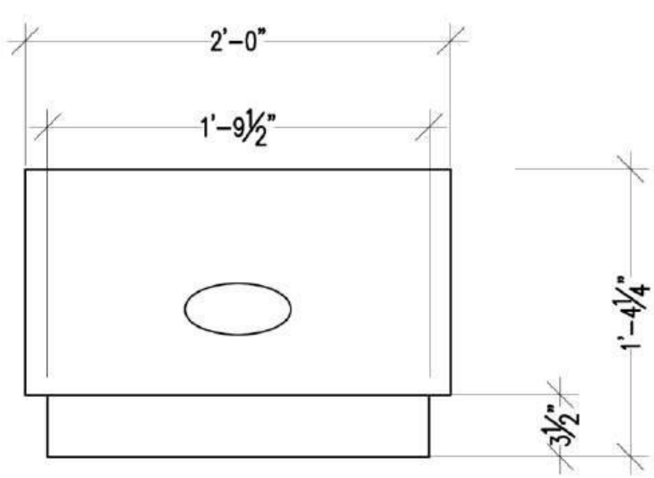
Dense-packer Construction Details

Figure D-9: Top View



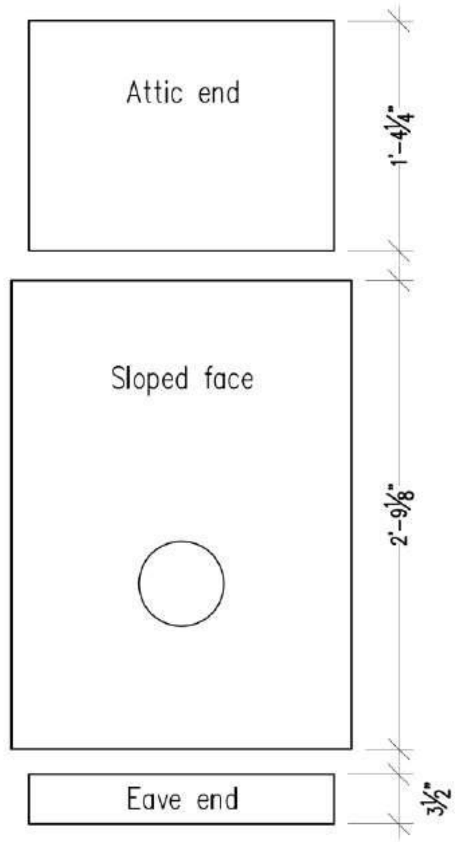
Source: The Levi Partnership, Inc.

Figure D-10: Front View



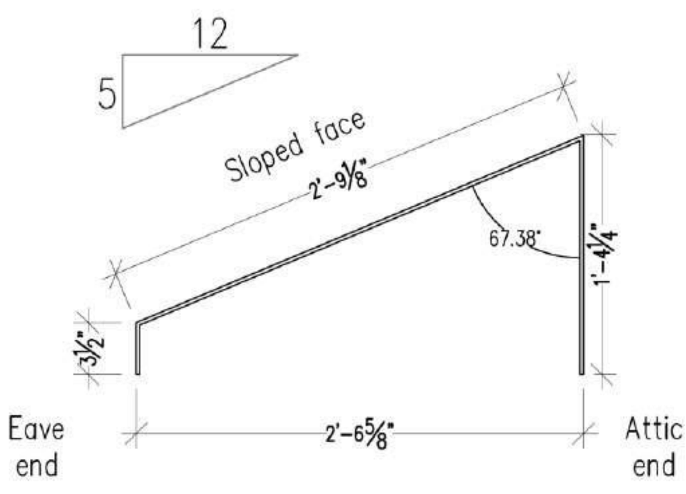
Source: The Levi Partnership, Inc.

Figure D-11: Surface Area Development



Source: The Levi Partnership, Inc.

Figure D-12: Side Elevation

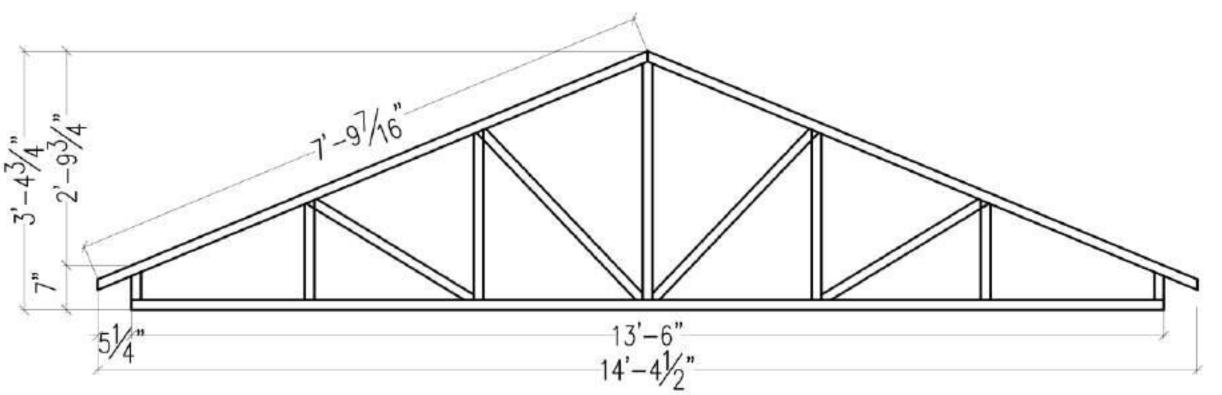


Source: The Levi Partnership, Inc.

Truss Designs

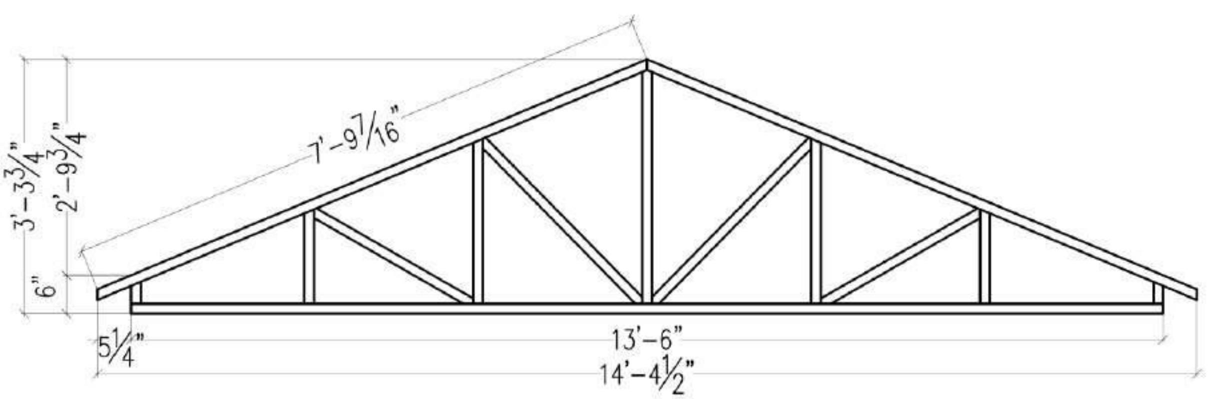
Figure D-13 and Figure D-14show the design and dimensions of the two truss types used in the testing structure. Truss design T1 has a heel height of 6.5” and will be used in Designs 1 and 2, the Base case and the adjoining buffer bay. Truss design T2 has a lower heel height of 5.5” and will be used in the remaining two design bays and the end buffer zone.

Figure D-13: Truss Design - T1 (Buffer / Base / Design 1 / Design 2)



Source: The Levi Partnership, Inc.

Figure D-14: Truss Design - T2 (Design 3 / Design 4 / Buffer



Source: The Levi Partnership, Inc.

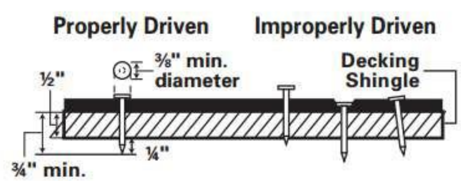
Appendix E: Roof Laboratory Testing, Phase 2 – Details

Installation Instructions – Owens Corning Cool Roof Shingles (Cool roof option 1)

Installation instructions: Application of Duration Premium Shingles

- Use extra care in handling shingles when temperature is below 40˚F
- Store in a covered, ventilated area at a maximum temperature of 110˚F. Stack in a flat fashion (maximum of 13 bundles high). Protect shingles from weather when stored at the job site. Do not store near steam pipes, radiators, etc
- Nails must be corrosion-resistant, 11- or 12-gauge, with heads at least 3 ⁄8" in diameter. Staples must be 16-gauge minimum, 15⁄16" minimum crown width, and sufficient length to penetrate 3 ⁄4" into wood decking or through APA-rated roof sheathing. Staples are to be corrosion-protected.

Figure E-1: Fastener Requirements



- All fasteners must penetrate at completely through sheathing.
- Owens Corning recommends the use of nails as the preferred method of attaching shingles to sheathing or other nailable surface
- Roof surface may be slippery, especially when wet or icy. Use a fall protection system when installing. Wear rubber-soled shoes. Walk with care
- WeatherLock® Underlayment or equivalent eave and flashing membrane should be applied to a point at least 24'' beyond interior wall line, where required by code.
- For low slope (2” in 12” to less than 4” in 12”) application of underlayment and metal drip edges should be as seen below. Apply a 19”starter strip of underlayment over metal drip edge at eaves. Use only enough fasteners to hold it in place. Use 36” strip of underlayment for remaining courses, overlapping each course by 19”. Side laps are to be staggered 6” apart. Apply metal drip edge over underlayment at eaves.

Figure E-2: Specialty Eave Flashing

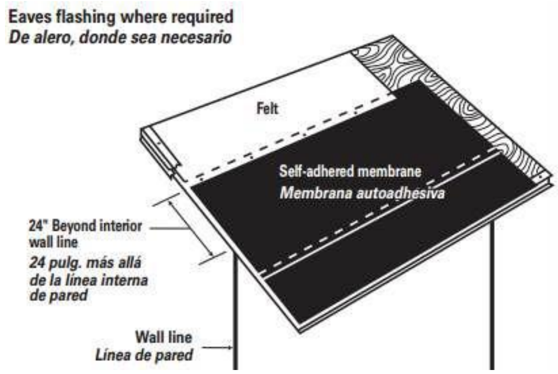
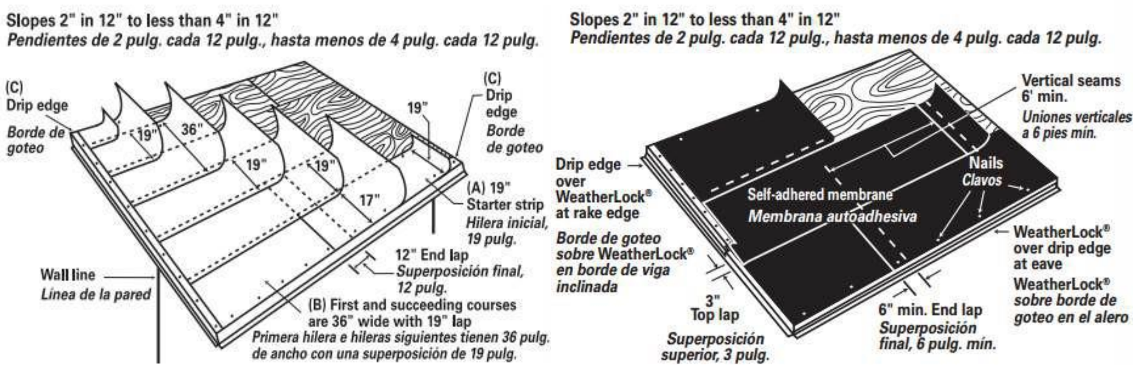
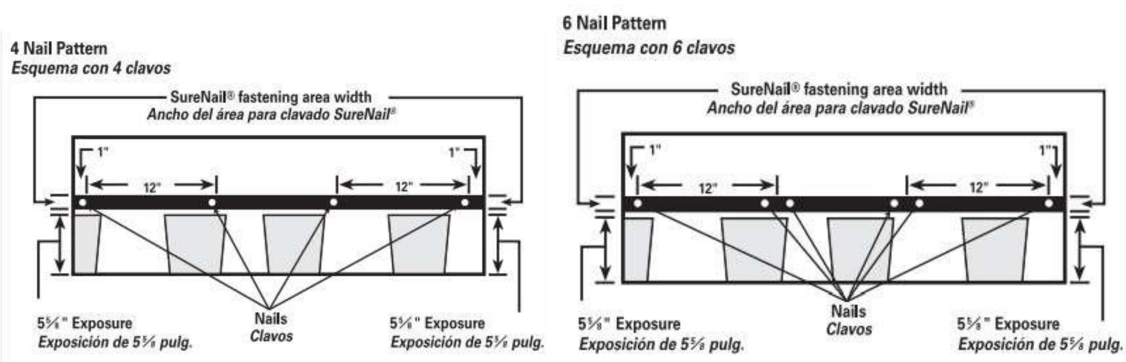


Figure E-3: Underlayment for Low Slope



- Shingle Fastening could be done in either of the two ways- 4 Nail fastening pattern and 6 Nail fastening pattern. Fasteners must be placed in the SureNail(R) fastening area.

Figure E-4: 4 Nail fastening pattern (L), 6 Nail fastening pattern(R)



- Follow general shingle application guidelines. http://www.owenscorning.com/NetworkShare/Roofing/10014283-TruDefinition%C2%AE- Duration%C2%AE-Series-Shingles-Installation-Instructions.pdf

Installation Instructions – TopGard4000 (Cool roof option 2)

Installation instructions: Application of TopGard4000

- Apply when temperature is 50˚F (10˚C) and rising.
- When TopGard4000 is used over asphalt, modified bitumen and single ply roofing systems, TopGard Base Coat must be applied prior to the application of the TopGard 4000.
- It can be used within 24 hours of roof membrane installation when used with TopGard Base, except when used over a cold applied modified bitumen roofs.
- TopGard Base Coat should not be installed over a cold applied SBS or APP roof until the adhesive is fully cured.
- When using TopGard 4000 in conjunction with TopGard Base Coat, the TopGard Base Coat must be applied first at a 20 wet mil thickness and allowed to dry completely (normally 4-12 hours) prior to the application of the TopGard 4000.
- When applying TopGard 4000, use a brush, roller or spray equipment. Make sure that all surfaces are clean, dry and free of any dirt, grease, oil or other debris that may interfere with proper adhesion.
- It is recommended that TopGard 4000 be applied in two coats. The first coat should be completely dry (normally 4 to 12 hours) before applying the second coat.
- Each coat should be applied at a wet mil thickness of 20mils (0.02").
- Do not apply TopGard 4000 within 24 hours of anticipated rain, dew or freezing temperatures since it will slow the cure time.
- Precautions - Avoid prolonged contact with skin and eyes. Keep container closed when not in use.

Installation Instructions – LP Tech Shield

Storage & Handling:

- Store LP TechShield panels in a clean, dry area. Do not store in direct contact with the ground
- Use caution to avoid damage to the radiant barrier foil surface.
- Roof Sheathing Installation:
- Provide ¾” minimum air space between the sheathing and the insulation.

- Place the skid-resistant side up with the APA trademark stamp facing down and wear skid- resistant shoes when installing the roof sheathing (Foil side facing the attic).
- Install with the long dimension or strength axis of the panel across supports and with panel continuous over two or more spans.
- Provide 1/8" minimum space at panel ends and edges. Use a spacer tool (i.e. 10d box nail) to assure accurate spacing.
- Panel end joints shall occur over framing. Stagger end joints in each succeeding row
- Provide additional panel stiffness by installing panel edge clips mid-span and on all unsupported edges.
- Nail 6" o.c. along the supported panel ends and 12" o.c. at intermediate supports. Fasten panels 3/8" from panel ends. Use 8d common nails for panels up to 1" thickness. Other code approved fasteners may be used.
- Cover roof sheathing as soon as possible with roofing felt or shingle underlayment for protection against moisture prior to roofing. I any edge swelling occurs prior to roof underlayment installation, all raised joints should be sanded flat.
- Allow sheathing to adjust to humidity and moisture conditions before shingle installation
- Remove wrinkles and flatten surface of shingle underlayment before installing shingles. High performance shingle underlayment is recommended for better results.

Appendix F: Technology Transfer Activities

2017 CMHI Annual Convention
March 15-16, 2017

Next Generation Energy Technologies:
California Leads the Way

Emanuel Levy

Advanced Walls Prototyping

Prototyping hosted by
Karsten Homes, Sacramento, CA
(October 2013)

4

Next Gen CoreTechnologies

- ✓ Dense-packed blown fiberglass insulation
- ✓ Exterior foam sheathing on the walls
- ✓ Cool roof technologies (radiant barriers and reflective surfaces
- ✓ High performance windows

and

- ✓ Ductless mini-split heat pumps

2

Advanced Roof Prototyping

Prototyping hosted by
Golden West Homes, Perris, CA
(October 2014)

5

Advanced Walls Prototyping

Prototyping hosted by
Fleetwood Homes, Riverside, CA
(February 2013)

3

Cool Roof Prototyping

Prototyping hosted by
Fleetwood Homes, Riverside, CA
(May 2015)

6

Dense-Packing Roof Insulation

7

Energy Cost Savings*

Location	Electrically-heated Homes: Standard Home Total ($ /yr)	Electrically-heated Homes: Advanced Envelope Total ($ /yr)	Electrically-heated Homes: Savings ($ /yr)	Gas-heated Homes: Standard Home Total ($ /yr)	Gas-heated Homes: Advanced Envelope Total ($ /yr)	Gas-heated Homes: Savings ($ /yr)
Arcata	$ 1,487	$ 758	**$ 730**	$ 516	$ 269	**$ 247**
Santa Rosa	$ 833	$ 423	**$ 410**	$ 328	$ 184	**$ 144**
Oakland	$ 665	$ 288	**$ 376**	$ 239	$ 111	**$ 128**
San Jose	$ 707	$ 313	**$ 394**	$ 284	$ 158	**$ 126**
Sacramento	$ 1,037	$ 592	**$ 445**	$ 489	$ 282	**$ 207**
Fresno	$ 1,229	$ 764	**$ 464**	$ 739	$ 475	**$ 265**
Palmdale	$ 1,214	$ 690	**$ 524**	$ 698	$ 435	**$ 263**
Palm Springs	$ 1,264	$ 896	**$ 369**	$ 1,222	$ 883	**$ 338**
Blue Canyon	$ 2,139	$ 1,291	**$ 848**	$ 775	$ 487	**$ 289**

*** Savings does not include mini-split heat pumps**

10

Whole Home Prototyping

Prototyping hosted by
Skyline Homes, Woodland, CA
(May 2015)

8

Ductless Mini-Split Heat Pump

11

Whole Home Prototyping

Prototyping hosted by
Golden West Homes, Perris, CA
(December 2016)

9

Ductless Mini-Split Heat Pump

- ✔ Cost competitive with existing systems
- ✔ Extremely high efficiency
- ✔ Factory installed and charged
- ✔ NO DUCTS, no site work
- ✔ Transfer fans, individual zone thermostats
- ✔ No furnace taking up floor space

Performance metrics	Conventional ducted heat pump	Advanced ductless heat pump
Heating efficiency (HSPF)	7.5	9.0
Cooling efficiency (SEER)	13.0	22.0

12

Side-by-Side Tests

The 2007 Energy Act

- **Requirements**: *"…standards .. shall be based on the most recent version of the IECC… except in cases in which …the code is not cost-effective.."*
- **Considerations**: *"… standards may take into consideration the design and factory construction of manufactured homes; be based on the (HUD) climate zones rather than the (IECC) climate zones; and provide for alternative (compliance) practices …"*
- **Updating**: *"…standards shall be updated not later than one year after the date of enactment of this Act; and one year after any revision to the IECC."*

Impact on Home Performance

Case	U_o-value	Energy savings compared to basic
Basic Home • Code compliant construction	0.116	--
Zero Energy-Ready Home (wo/HP) • Walls: Stud walls with exterior insulation • Roof: Dense-packed insulation at eaves • Floor: High performance floor • Windows: High performance, argon filled	0.063	46%
Zero Energy-Ready Home • Advanced envelope features with mini-split ductless high performance heat pump	0.063	76%

California Energy Commission Case Study

Cool Roofs in California: Energy-Saving Strategies for Manufactured Homes

PROJECT INFORMATION

Project Name: **Cool-Roof Strategies to Reduce Cooling-Energy Use in Manufactured Homes**

Building Component: **Roof**

Test Conditions: **Prototype testing**

TECHNICAL LEAD

The Levy Partnership, Inc., levypartnership.com

PARTNERS

AFM Corp.

Atlas EPS

BlueLinx Corp.

California Manufactured Housing Institute

CAVCO Industries—Fleetwood Homes, Inc.

Dow Chemical Co.

FAMCO

Golden West Homes—Clayton Homes, Inc.

Hallmark Southwest Corp., Inc.

Johns Manville

Karsten Homes—Clayton Homes, Inc.

LP Corp.

Owens Corning

SENCO Products

Service Partners

Skyline Homes, Inc.

Systems Building Research Alliance

To reach California's goal of net-zero energy in new residential buildings by 2020, builders are employing innovative construction practices and technologies. In a joint effort funded by the California Energy Commission, a team of building-science professionals, product suppliers, and factory homebuilders developed and tested several innovative energy-saving techniques to move manufactured homes toward the ambitious goal of zero energy use by the year 2020. Included in the package of energy-saving strategies are "cool roof" strategies that significantly reduce air-conditioning needs in areas of California that experience long, hot summers.

"Cool roofs" are roof assemblies that reflect the sun's energy instead of absorbing it, keeping the indoor temperature of the home cooler even on the sunniest, hottest days of the year.

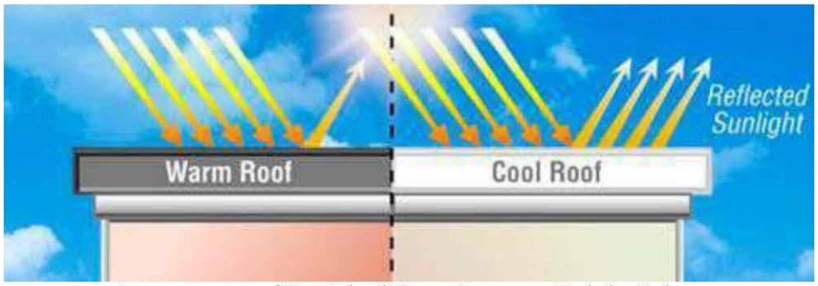


Image courtesy of Heat Island Group, Lawrence Berkeley Laboratory

Two cool-roof strategies were included in the study:

a) **Radiant barrier**: a layer of reflective foil-type material installed within the attic that inhibits the sun's radiant heat from reaching the home's interior; and

b) **Cool-roof coverings**: light-colored and reflective roof coatings or materials applied to the exterior of the roof surface

FINDINGS

Reduction in Summer Roof Temperature: Up to 40˚F

Cooling-Season Energy-Bill Savings: Up to $116*

* Savings based on $0.18/kWh electric utility rate and a 1,530-s.f. home; subject to climate.

KEY DETAILS

Out of three shingle types tested in Riverside, CA, white shingles showed superior abilities to moderate attic temperatures on hot summer days.

Test roof structure in Riverside, CA

The tests conducted included assessing how different colored roof finishes influence attic temperatures. In general, the lighter the roof color, the greater the cooling season savings.

Home with Cool Roof

Tests showed that combining a radiant barrier with cool-roof shingles improves the effects of both strategies, saving even more in cooling energy.

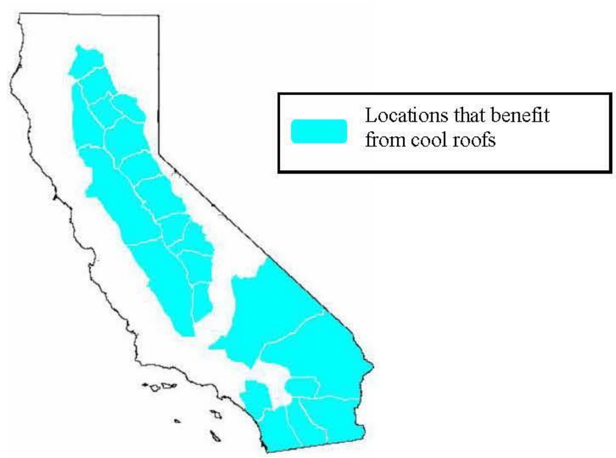
reflecting more of the sun's energy keeping the surface of the roof cooler.

Several types of cool roofs were tested at Fleetwood Homes in Riverside, CA, including light-colored and white shingles (left). The tests also evaluated the benefits of radiant barriers.

These tests revealed that cool-roof coverings can save as much as **$116 over the course of the summer**. A radiant barrier in the attic can save between $30 and $70 each summer. Combined, the cool-roof strategies can save even more.

Compared to a standard roof, attic temperatures in cool roofs were as much as **40˚F cooler** on hot days, with significant air-conditioning savings.

Title 24 encourages the use of cool roofs for homes in areas with high air-conditioning requirements (see map below). This research confirmed that manufactured homes in these locations save on space-conditioning with cool roofs, **saving between $50 and $116 each year**. Cool roofs are not recommended in colder climates, however, as solar heat can help reduce heating needs in these locations.



California Energy Commission Case Study

Advanced Envelope Technologies in California: Energy-Saving Strategies for Manufactured Homes

PROJECT INFORMATION

Project Name: **Advanced Envelope Systems for Factory Built Homes**

Building Components: **Wall and Roof**

Test Conditions: **Prototype and Full-Scale Testing**

TECHNICAL LEAD

The Levy Partnership, Inc., www.LevyPartnership.com

PARTNERS

AFM Corp.

Atlas EPS

BlueLinx Corp.

California Manufactured Housing Institute

CAVCO Industries—Fleetwood Homes

Custom Homes of Jamestown, CA

Dow Chemical Co.

FAMCO

Golden West Homes—Clayton Homes

Hallmark Southwest Corp., Inc.

Johns Manville

Karsten Homes—Clayton Homes, Inc.

LP Corp.

Owens Corning

SENCO Products

Service Partners

Skyline Homes, Inc.

Systems Building Research Alliance

The manufactured housing industry has joined the push to reach California's goal of net-zero energy use in new residential buildings by 2020, developing and adopting innovative construction practices and technologies. In a joint effort funded by the California Energy Commission, a team of building-science professionals, product suppliers, and factory homebuilders developed and tested several innovative energy-saving techniques that move manufactured homes toward the zero-energy use goal. Through major savings in energy costs, the strategies reduce the overall monthly cost of homeownership, while improving comfort.

While "advanced" from the standpoint of current methods of home building, the technologies employ off-the-shelf products and components that home manufacturers can use today. The effort focused on reducing energy losses through the walls and roof by applying innovative insulation methods, referred to as "Advanced Envelope Technologies."

Advanced roofs consist of densely packed blown insulation at the roof eaves and sloped roof cavity sections, with standard density insulation elsewhere in the attic. Increasing insulation density in the most constricted parts of the attic improves thermal performance, reducing home heating and cooling energy requirements.

Advanced walls start with standard wall construction but add a continuous layer of highly insulative sheathing underneath the siding. This uniform layer of insulation both adds more insulation value and makes the home more weather-tight.

FINDINGS

Average Energy-Bill Savings:

$180/year in gas-heated home
$390/year in electrically heated home

Net Savings (Cost/Benefit):

$1,350 in gas-heated home
$2,325 in electrically heated home

Savings based on $0.18/kWh electric utility rate and a 1,680-s.f. home

Estimates of net savings assume 20-year mortgage term, 10% down payment, and 9% interest rate

KEY DETAILS

Out of several roof-insulation strategies tested, dense-packed eaves in a vented roof demonstrated the best performance in terms of energy savings, comfort, and durability.

Full-scale roof test at Golden West/Perris

A small test structure was built in Jamestown, CA to assess the performance and potential energy benefits associated with the innovative wall and roof assemblies. Once the technologies were proven to work, examples of the advanced wall and roof assemblies were built by project partners Karsten Homes/ Sacramento, Skyline/Woodland and Golden West/Perris, CA.

Full-scale Advanced Wall build at Karsten Homes

Wrapping the home like a blanket, foam-sheathed walls proved to be a reliable thermal barrier that was easy to include during the construction process. The dense-packing of insulation in the roof allows home manufacturers to effectively insulate a part of the home must vulnerable to energy loss, especially for homes with vaulted and cathedral ceilings with little area to insulate.

More eave insulation translates into a higher average insulation value for the home, saving energy and allowing the use of smaller, less expensive heating and cooling equipment. Together, the advanced walls and roofs save on average between $150 and $400 per year in utility costs

Demonstration Home Build

A demonstration home build with the advanced wall and roof assemblies was conducted on March 21, 2017 at the manufacturing home facilities of Golden West Homes, Perris, California, which is a subsidiary of Clayton Manufactured Homes. The sections below discuss the production process of the demonstration home that incorporated the advanced wall and roof technologies.

The advanced technologies were installed on a multi-section manufactured home on the production line. The chosen home consisted of two sections, 12' wide x 48'0" long and 8' high, with a cathedral ceiling and trusses spaced at 24" on center. The specifications for the advanced assemblies are given in Table F-1.

Table F-1: Specifications for the Advanced Wall and Roof Assemblies

Item	Specifications
ROOF CONSTRUCTION	
Roof design	Vented Attic Roof with dense-packed blown FG insulation at eaves and standard blown insulation in the attic
Description	Dense-pack blown FG insulation in the eaves of the attic roof to increase the thermal performance of the roof and standard density blown FG insulation unrestricted in the attic
Roof frame	24" O.C
Insulation	Blown in Climate Pro FG Insulation
Ventilation	1" air gap along the roof slope by means of cardboard baffles
EXTERIOR WALL CONSTRUCTION	
Wall design	Stud walls with continuous exterior insulation
Description	Continuous exterior rigid insulation to increase the thermal performance of the wall system
Wall framing	16" O.C
Frame cavity insulation	FG faced Batts
Exterior continuous insulation	1" R-5 EPS board

Production Process

This build was conducted as part of the technology transfer activities intended to disseminate research findings to the manufactured housing industry. The objective of the build was to evaluate the production aspects, such as inventory and equipment, which were impacted by the incorporation of the advanced wall and roof designs into the manufactured home. The production process comprised of the following steps:

Step 1. Plant inventory: Sourcing of materials

Roofs:

- **Blown fiberglass insulation (Johns Manville)** was sourced for dense packing. The details of the insulation are shown in Table 55.

- **Baffles (23" X 24")** were procured for ventilating the attic roofs. The size and configuration of the baffles chosen was based on the spacing of the truss bays and the area of dense packing.
- **Fasteners, staples and staple guns (SENCO)** required for the installation of siding were obtained.

Walls:

- **1" thick EPS foam insulation boards, 10' X 4' (ATLAS EPS)** were procured for the wall assembly. The physical properties of the boards are shown in Table F-2.

Table F-2: Physical Properties of Insulation Products

Item	Property
EXTERIOR CONTINUOUS INSULATION ON WALLS	
Insulation brand name	Atlas Thermal Star X EPS GX 25
Insulation type	Expanded polystyrene Rigid Foam or EPS
Manufacturer	Atlas EPS
Product thick. @ R-5	1"
Perm rating @1"	Class III (2 perm)
Compressive strength	25 psi
Panel size	120" X 48"
ROOF CAVITY INSULATION	
Insulation brand name	Climate Pro® Blow-In-Blanket® System
Insulation type	Loose fill fiberglass insulation
Manufacturer	Johns Manville
Standard installed density (estimated)	0.76 lbs/ft^2
Dense-packed installed density	1.5 lbs/ft^2
Available bag size	31.5 lbs/bag

Step 2. Code compliance and DAPIA approval

- Both, wall and roof products and materials, used in the envelope construction meet the HUD code requirements.
- DAPIA approval was also obtained and minor changes were made to the construction details of the soffit vent to incorporate the foam boards.

Step 3. Actions taken at the plant

Roofs:

- The blowers were recalibrated for fiberglass insulation since the plant currently uses cellulose. This transition was observed to be smooth and no major issues were identified with switching to blown fiberglass.
- The dense-packing mold was fabricated based on roof specifications using pegboards, nails, handles and supports, which are standard materials that are available at the plant.

Walls:

- The foam boards were cut to the required size using standard cutters so that they were appropriate for the height of the home.

Step 4. Procurement of tools and fasteners

Since the foam boards add to the width of the wall assembly, longer fasteners, staples and compatible staple guns were required for installing the boards. The fastening schedule for stapling the continuous exterior insulation to the frame and nailing the siding is: one every 6 in. along the perimeter and one every 12 in. in the field. The fasteners utilized in the wall installation are given in Table F-3

Table F-3: Fastening Schedule

Product brand name	Description
Senco 2” x 1” crown 16 gauge staple	Insulation staple
Senco 3” x 0.120 RS Nail	Siding nail
16 gauge, 1” wide crown, 2” heavy wire stapler	Staple gun
4” 34 clipped head framing nailer	Nailing gun

The routing of doors and windows was done twice, at the foam and at the siding. Ideally a router bit with a longer cutter could have been used to cut both, the foam and the siding, in a single step saving time and labor.

Step 5. Training of plant staff

Before the installation of the advanced assemblies, the staff was familiarized with the following:

- Method of dense packing the eaves using the mold
- Installation of baffles to maintain the air space

Cutting, installation and taping of the foam boards follow typical processes at a factory home-building production facility.

Step 6. Installation of advanced envelope assemblies

Roof:

All roof insulation tasks were performed by the roof insulation crew after plumbing, electrical, and HVAC tasks were completed in the roof. The molds used to install insulation were key elements of process re-tooling. The general flow consisted of the following tasks: install baffles at eaves, install insulation at eaves, install baffles along rafters, and install insulation in field.

Tasks were performed at various times by one to two workers working simultaneously. All tasks were performed on roof trusses except for installing baffles at eaves, which was performed on scaffolding.

Figure F-1: Dense-packing of Roof Insulation Using a Mold

Source: The Levy Partnership, Inc.

Figure F-2: Dense-packed Fiberglass Insulation at Eaves

Source: The Levy Partnership, Inc.

Figure F-3: Baffles Installed to Maintain 1" Air Gap

Source: The Levy Partnership, Inc.

Walls:

The wall insulation tasks were performed by the crew at the floor level as well as on the movable scaffolding. The general flow consisted of the following tasks: cut and place the boards on the studs, staple the boards, cut out openings, staple around the openings and tape all seams. The boards were installed from the center of each wall to the corners, with one to two workers working simultaneously.

Figure F-4: Cutting 10' Foam Boards to 8' Height

Source: The Levy Partnership, Inc.

Figure F-5: Installing Foam Boards and Stapling

Source: The Levy Partnership, Inc.

Figure F-6: Routing of Openings in Foam Board

Source: The Levy Partnership, Inc.

Figure F-7: Taping Rigid Foams at Seams

Source: The Levy Partnership, Inc.

Figure F-8: Installing Siding over Foam Board

Source: The Levy Partnership, Inc.

Figure F-9: Layers of Wall Assembly

Source: The Levy Partnership, Inc.

Figure F-10: Routing of Openings in Siding

Source: The Levy Partnership, Inc.

Recommendations

Implementation of the advanced wall and roof technologies on the demonstration home at the Perris Plant was conducted successfully, without facing any hurdles. The following recommendations can be made based on the observations made by the research team and the plant staff during the build.

Roof

- Short (23") cardboard baffles are easy to install, less laborious and easy to modify (when
- required at certain bays).
- A well fabricated mold is vital in the dense packing process. Using a mold which covers multiple bays at a time could reduce the time required to lift and place mold in next bay.
- The routing of openings done twice at the foam board and the siding could cause production delays. Longer router bits should be utilized, to save on the time and labor needed.

Walls

- The exterior wall height, including the rim joist, was about 8 ft. but the EPS panels were 4 ft. x 10 ft. sheets. This resulted in the need to cut them accordingly, a step that can be eliminated by the use of boards that are appropriate to the home height.
- The width of the foam boards supplied by the insulation manufacturer was a little short of 48 in (likely due to a fabrication error). This was assumed to be an isolated manufacturing error, which could be avoided.
- Corner framing detail should be handled well without creating a thermal bridge. The rigid foam insulation was trimmed to overhang the end by 1 in. catching the adjacent board and providing a tight foam seal around each corner.